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Remote Data Acquisition and Error Analysis of the Scattering Parameters of Quartz Crystal Devices

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REMOTE DATA ACQUISITION
AND ERROR ANALYSIS OF
THE SCATTERING PARAMETERS
OF QUARTZ
CRYSTAL DEVICES

BY

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ABSTRACT

A two-port device can be described by the incident and reflected voltages at each port. The parameters used in this description are known as scattering parameters. Accurate measurement of the values are thus important in device evaluation and network design.

Limitations arise with the measurement capability of the equipment. In order to reduce these limitations, the data acquisition is controlled remotely by a computer program. The program also offers an error correction analysis of the measurement results.

The measurement setup and basic approach are discussed as well as the techniques of normalization and calibration of each scattering parameter. The computer program offers three methods of data acquisition which are presented in detail. Results of device testing and error analysis are presented.

ACKNOWLEDGMENTS

I would like to take this opportunity to express my gratitude to my advisor, Dr. Donald Malocha, for his unending guidance and support throughout the interim of my electrical engineering studies. He always ascertained the areas of my scholastic weaknesses and urged me towards self-improvement in those areas. Dr. Malocha holds my ineffable admiration and I will always think of him with the warmth of friendship.

Many thanks are also due to Carlton Bishop who became, through no fault of his own, my mentor in the field of computer programming. I found his expertise to be nonpareil and indispensable.

Both of these gentlemen should be highly commended for their patience and sense of humor.

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INTRODUCTION

The importance of quartz crystal resonators in electronics results from their extremely high quality factor, relatively small size, and excellent temperature stability [1]. Surface acoustic wave filters offer the advantages of inherent linear phase, superior shape factors, excellent rejection, small size, and high repeatability [2].

The use of quartz crystal units in frequency control, filter and timing applications require accurate determination of the value of their equivalent electrical parameters. For the measurement of these parameters, the single-port reflection method characterizes the crystal device as a two-terminal unit and provides very accurate determination of resonance frequency and resistance as well as motional-arm parameters [3].

While the measurement of the scattering parameters, with their normalization and calibration, follows the standard reference method of measurement of the parameters of crystal devices, the actual data acquisition is performed remotely by computer. A program was written that offers the user much greater freedom in specification of acquisition characteristics than utilization of the network analyzer and S-Parameter test set only. With this freedom, the user may define the desired number of data acquisition points or the desired delta frequency, may make an error analysis, and may obtain permanent records of the device measurement in printed and plot form and by transfer of the data to hard disc for future manipulation.

The objective of the project was to write a computer program for testing of quartz crystal devices. As stated, the program provides a remote acquisition of all scattering parameters and a means of error analysis.

PROPOSED STRATEGY

Data Acquisition

The operation of the HP 3577A Network Analyzer and the HP 35677A S-Parameter Test Set from the front panel limits the user in several ways. First of all, the maximum number of sample frequencies available across the screen is 401. This is due to the sweep resolution of the network analyzer. The user may select 51, 101, 201, or 401 points per sweep, compromising fewer trace points for a shorter sweep time [4]. The second limiting factor of operation from the front panel is the exact measurement values can only be found by moving the marker across the trace and noting the magnitude, phase, and frequency values printed at the top of the screen. This procedure becomes tedious if more than a few values are needed. Thirdly, the only permanent record of device measurement available is by use of the HP 7475A Plotter. By making a plot, the user has a record of the value of the single magnitude and single phase for the marker frequency. All other values must be approximated by noting the scaling factors. Fourthly, the method of error analysis is obtained by taking two sets of measurements and noting the difference in the printed marker values for one particular frequency.

A method of data acquisition was needed that would allow the user the option of choosing the desired sweep resolution; that is, of choosing from any number of data points. This method should also offer, in a concise manner, exact values of magnitude and phase for each of the measured frequencies with the option of a permanent record. Also a method of error analysis should be incorporated in the device measurements.

The method of data acquisition chosen was a computer program which would remotely control the Network Analyzer to take measurements from the device under test using user input specifications.

Since the network analyzer has a limitation of points per sweep, the computer program should be able to measure any number of points per sweep. The program should be able to perform the necessary mathematical calculations to normalize or calibrate each of the scattering parameters.

The equipment to be used is the HP 3577A Automatic Network Analyzer, the HP 35677A S-Parameter Test Set, the HP 9845B Computer, the HP 9133 Disc Drive, and the HP 7475A plotter. These are interconnected via the HP Interface Bus.

Data messages are sent from one machine to another on the bus in an 8-bit parallel, byte serial manner using standard ASCII codes. Only one machine at a time can place information on the data lines of the bus and that machine is known as the active talker. Another machine, known as the active listener, senses the information on these data lines and acts on that information. The computer program must instruct the network analyzer to be a listener so that it can be set up for measurements and told when to take readings. It then must be made a talker so that it can put the results of that reading on the data bus to be sent back to the computer for calculations. Plotting will be done by defining either the plotter or the computer screen as the plotting device and then sending the data and instructions to the plotting device directly from the computer. Complete specifications of the destination for messages and data transfer will be accomplished by machine addresses [5].

The computer program should be fairly general in order to control the network analyzer to test a wide range of devices. Interest will focus, however, on quartz crystal resonators and acoustic filters.

Sensitivity Analysis

Inherent in the HP Network Analyzer are accuracy and frequency response errors which must be compensated. In the S-Parameter test set are frequency response, port match, and test port reciprocity errors which also must be compensated. Specifications are found in Appendix A [4].

The computer program should offer the option of making two measurement sweeps for each scattering parameter. The errors will be found by subtracting the polar values of the second sweep from the first. Perfectly accurate results would then yield errors of 0 dB and 0 degrees. Deviation falling outside the range of the network analyzer specifications should then be treated as extrinsic errors. Possible causes for these extrinsic errors will be discussed later.

METHODS, PROCEDURES, AND EXPERIMENTS

Basic System Setup

The 3 1/2 inch disc labelled "Scat" is inserted into the disc drive. The command MASS STORAGE IS ":A6" is executed. This specifies the mass storage operations be directed to the disc drive. The user then executes the command GET "SCAT:A6,2" to load the program into the computer [6].

The program is executed by the RUN or CONTINUE key. The measurement setup begins with the OPTION BASE 1 command which specifies that the lower bound for array dimension be one rather than zero. This assures that the array dimensions will be matched to the measurement FOR/NEXT loops. The screen prompts the user to press the SPECIAL FUNCTION hardkey and then the TALK ONLY OFF softkey on the network analyzer. This enables the network analyzer to be a listener on the bus [6].

The next command is REMOTE 711 which switches device number eleven (network analyzer) on port seven (HP IB) from local to remote control [6]. Sixteen arrays are initially dimensioned to hold 1024 data points. A maximum of eleven arrays are utilized with the scattering parameters S_{21}, S_{12}, and S_{22} depending upon error sweeps and plots. The scattering parameter S_{11} utilizes all sixteen arrays. The

INSTRUMENT PRESET command is executed next. Default conditions utilized and unchanged by the program's measurement setup are included in Table 1.

TABLE 1

NETWORK ANALYZER INSTRUMENT CONDITIONS UTILIZED IN THE DATA ACQUISITION AND ERROR ANALYSIS PROGRAM

FUNCTION	CONDITION	SET BY
1. Display Function	Trace 1: log magnitude	Default
	(linear magnitude, V, for S_{11})	Program
	Trace 2: Phase, degrees	Program
2. Amplitude	-49 dBm to +15 dBm	User
3. Start Frequency	0 Hz minimum	User
4. Stop Frequency	200 MHz maximum	User
5. Sweep Type	Linear Frequency Sweep for "Dump the Screen" Data Acquisition,	Default
	Continuous Wave for "Define N" and "Define Df" Data Acquisition	Program
6. Sweep Time	1 second for Linear Frequency Sweep, 0.05 ms Sample Time for Continuous Wave Sweep	Default
7. Sweep Mode	Single Sweep for "Dump the Screen" Data Acqui-sition,	Program
	Continuous Sweep for "Define N" and "Define Df" Data Acquisition	Default
8. Sweep Resolution	401 points/span for "Dump the Screen" Data Acquisition,	Default
	2-1024 points/span for "Define N" and "Define Df" Data Acquisition	User
9. Trigger Mode	Free Run	Default
10. Resolution Bandwidth	1 kHz	Default
11. Averaging	Off	Default
12. Attenuation (input)	20 dB	Default
13. Impedance (input)	50 Ohms	Default

The user is prompted to enter the start frequency and stop frequency in MHz. The frequency range for the network analyzer is from 5 Hz to 200 MHz. However the frequency range for the S-Parameter test set is from 100 kHz to 200 MHz. Regardless, the program is designed to accept a start frequency of 0 Hz in order to prepare for S_{21} data acquisition from a surface acoustic wave device with data storage for future fast Fourier transform. This is accomplished by loading the first value of the data acquisition arrays with -100 dB and 0 degrees and the first value of the normalizing arrays with 0 dB and 0 degrees. The Array Start Variable is set at 2 so that subsequent data acquisition will begin at the incremented frequency and storage will begin at the second value of the arrays. If the start frequency had been other than 0 Hz the Array Start Variable will be set at 1 so that subsequent data acquisition will begin at the start frequency. Storage will begin in the first value of the arrays.

The user is prompted to enter a value for the signal level of the source output. Trace 2 is defined as phase in degrees. By default, Trace 1 is log magnitude.

The program then goes to the Data Acquisition Method Subroutine where the user is prompted to choose one of three methods of data acquisition. These methods are discussed in detail later in this chapter. The program returns to the Measurement Setup Section and the sixteen arrays are redimensioned to hold N number of data points, where N was defined in the Data Acquisition Method Subroutine.

The user is asked if dual sweeps for system error checks are desired. If so, the Error Run Flag is set. At this point the measurement setup is complete and the program progresses to the first scattering parameter.

Basic Approach and Block Diagram

The flow of the program after the Measurement Setup Section follows similar lines for each of the scattering parameters.

The user is asked if measurement of a particular scattering parameter is desired. If it is not, the program skips to the next parameter to ask the same question. When measurement is desired, a flag is set. This flag indicates throughout the generic normalization, printing, and plotting sections which scattering parameters the program is measuring. The program then goes to the Calibration Subroutine. If the scattering parameter is S_{21}, S_{12}, or S_{22}, the program goes to the Normalization Section of the subroutine. If the scattering parameter is S_{11} the program goes to the One Port Full Calibration Section of the subroutine. These normalizations and calibrations are discussed in detail later in this chapter. Measurements are taken using the calibration devices and stored in magnitude and phase arrays. The program returns to its scattering parameter section but then immediately goes to the Data Acquisition Subroutine. Measurements are taken from the device under test and stored in magnitude and phase arrays. The values are then normalized/calibrated. The program then goes to the 360 Degree Phase Shift Subroutine to compensate for phase shifts. The program returns to the Data Acquisition Subroutine and the Error Run Flag is checked.

If the flag is set, new measurements are taken from the device and are then normalized/calibrated using the same normalization/calibration measurements used previously. Systematic errors will thus be detected on test device measurements and not normalization/calibration device measurements. The phase array is compensated for any 360 degree shifts as before.

The values of the magnitude array and phase array are printed on the HP 9845B screen in decibels and degrees, respectively. If the Error Run Flag has been set the printed values are from the second sweep. The user is offered the option of having a hard print made of these values. If the Delta Frequency Method of Data Acquisition has been selected, the program goes to the Save Results Subroutine where the results, if the user desires, are saved on the disc drive for possible future Fast Fourier Transform.

The user is next asked if a normalized plot is desired. If so, the program goes to the Max_min Subroutine to find the maximum and minimum values for the vertical axis of the plot thereby "normalizing" it. The program then goes to the Plot Subroutine where plots of magnitude and phase can be made on the HP 9845B screen, the HP 7475A Plotter, or both.

The vertical axis gives the magnitude in decibels or the phase in degrees. The horizontal axis is the frequency span divided into ten sections with the center frequency labeled as "0.0" in the middle of the axis. The actual center of the frequency span is printed below the axis.

If dual sweeps for errors have been made, the second sweep is subtracted from the first. Data is in decibels and degrees. The magnitude and phase errors are printed on the HP 9845B screen and, as before, the user is offered the option of a hard print, saving the results (if the Delta Frequency Method of Data Acquisition has been selected), and making plots.

The program returns the particular scattering parameter section and the user is asked if the next scattering parameter measurements are desired. Progression is made through (or around) S_{21}, S_{12}, S_{11}, and finally, S_{22} before ending. The basic block diagram of the program is given in Figure 1.

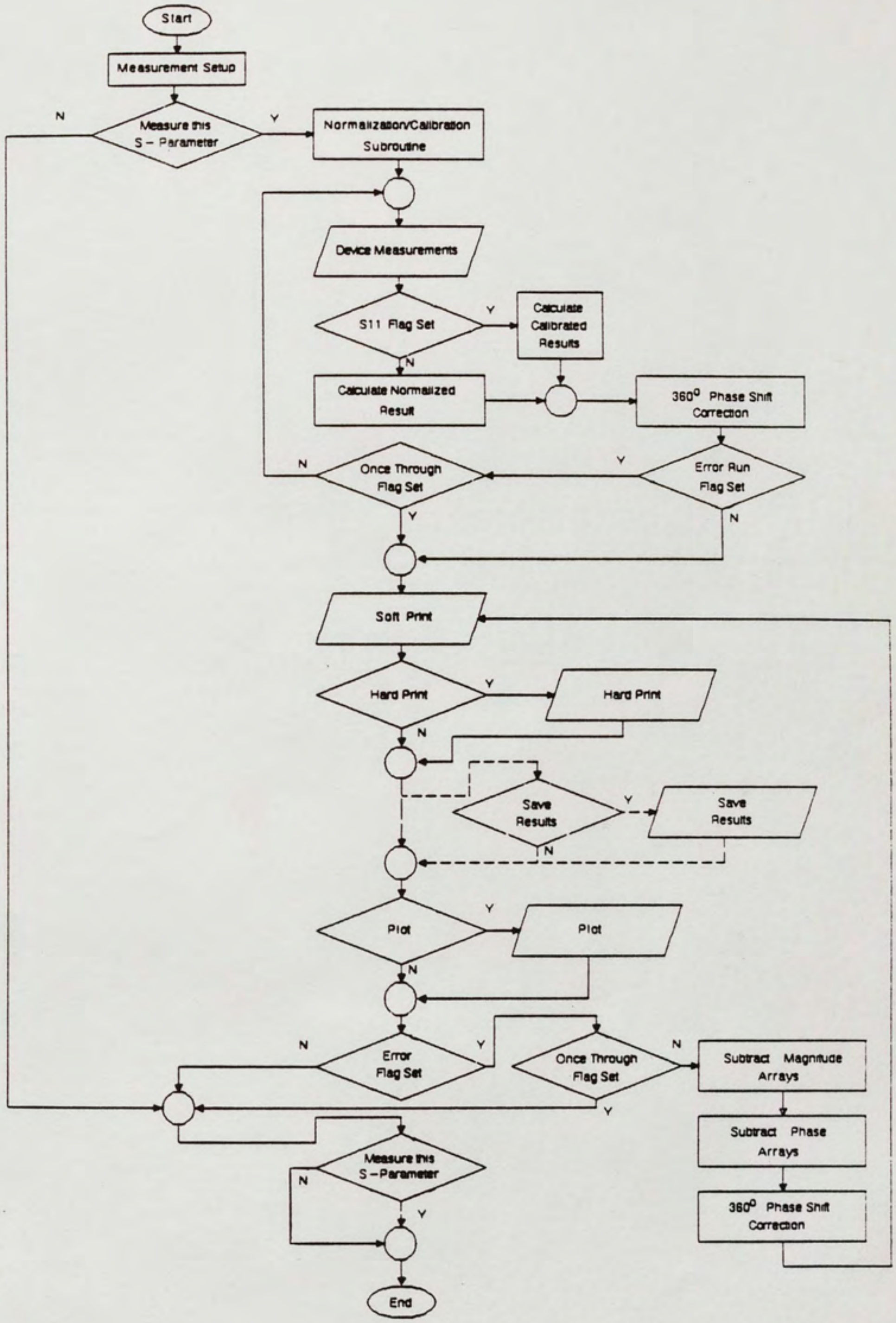

Figure 1. Basic Block Diagram of the Data Acquisition and Error Analysis Program

Measurements and Calibration

The measurement of the input reflection scattering parameter, S_{11}, is the most complex of the four parameters due to the mathematics of the calibration. In the S_{11} section of the program the magnitude function is changed from logarithmic to linear. The program then goes to the One Port Full Calibration Subroutine and the user is asked to insert an "Open" in the test fixture. The magnitude and phase measurements are taken, changed from polar to rectangular format, and stored in two arrays, Γ_{or} and Γ_{oi}. The user is then asked to replace the "Open" with a "Short." Again, measurements are made, changed to rectangular format and stored in arrays Γ_{sr} and Γ_{si}. The user replaces the "Short" with the reference load (fifty Ohms for the HP 35677A S-Parameter Test Set fixture) and, as before, the results are stored, this time in arrays Γ_{tr} and Γ_{ti}. The program then performs the first calculations necessary for calibration. Additional subroutines are called to change between polar and rectangular formats depending upon the actual mathematical operations. Polar format is utilized with multiplication and division so that the data can be added or subtracted in logarithmic form. The rectangular format is utilized with straightforward addition and subtraction of data. The correction factor for transmission, T_f, and the factor for source match, S_f, are calculated. The correction factor for directivity, D, is given by Γ_t. Directivity is the ratio of the reflected signal to the incident signal with the load in place. The user is asked to replace the "Load" with the device under test. The program then returns to the S_{11} section and is immediately sent to the Data Acquisition Subroutine. Device measurements, M_{meas}, are taken and the program goes to the end of the One Port Full Calibration Subroutine where they are first changed to rectangular format. Calculations continue, using the previously described Polar/Rectangular Subroutines, and the actual calibrated value for S_{11} is found using the equation [4]

$$S_{11} = \frac{M_{meas} - D}{S_f \cdot M_{meas} + T_f} \; .$$

An additional subroutine is called for plotting purposes, to correct for any 360 degree phase shifts. The final magnitude values are in decibels while phase is in degrees. A detailed derivation of the above equation can be found in Appendix B.

The remaining scattering parameters are not calibrated by the computer program but merely normalized. This fact needs to be taken into consideration by the user if true calibrated results are desired.

The forward gain and phase scattering parameter, S_{21}, is normalized by the use of a "Thru." The program leaves the S_{21} section and goes to the Normalizing Subroutine. The user is asked to insert a "Thru" into the test fixture and measurements are taken in polar format. The magnitude and phase values are stored in two arrays, D_n and E_n, respectively. The user is then asked to replace the "Thru" with the device under test. The program returns to the S_{21} section and immediately goes to the Data Acquisition Subroutine. Device measurements are made and the values are stored in arrays D and E. The polar format normalizing arrays are subtracted (linear division) from these arrays so that the final results are normalized against any variation from a transmission coefficient of unity. The phase is checked for a 360 degree shift before the results are printed on the HP 9845B screen.

The reverse loss scattering parameter, S_{12}, exactly follows the above procedure utilizing a "Thru."

The output reflection coefficient, S_{22}, varies from the above procedure only in that an "Open" is utilized to normalize against any variations from a reflection coefficient of unity.

Data Acquisition Methods

Near the completion of the Measurement Setup Section the program goes to the Data Acquisition Method Subroutine. The user is told the results of the measurements can be saved on the disc drive only by defining the delta frequency. The user is then prompted to choose one of the three methods of data acquisition. These methods are Dump the Screen, Define the Delta Frequency, and Define the Number of Data Points. The method of choice is then utilized in all subsequent normalizations/calibrations and measurements for each of the scattering parameters.

If the user chooses to dump the screen the "Dump the Screen" flag is set and the data point variable, N, which is used for array redimensioning, is given the value of 401. The program then returns to the end of the Measurement Setup Section. This method of data acquisition is limited by the fact that the maximum number of points available for measurement across the sweep is 401 due to the sweep resolution within the internal structure of the HP 3577A. For data acquisition, the default Sweep Type of Linear Frequency Sweep is utilized but the Sweep Mode is changed from the default selection of Continuous to Single Sweep. Thus a single sweep is made over the default Sweep Time of 1.0 second [4].

The next command is Take Measurement. The HP 3577A settles (by default, this settling time is 22ms [4]) and takes the measurement before processing the Dump Trace command thereby guaranteeing that the measurement will be completed before data transfer begins. Dump Trace 1 dumps the magnitude trace in logarithmic form for the scattering parameters S_{21}, S_{12}, and S_{22} and linear form for the scattering parameter S_{11}. Dump Trace 2 dumps the phase trace in degrees for all the scattering parameters. The data is then loaded into two separate arrays using formatting commands.

If the "Define the Delta Frequency" method of data acquisition is chosen, that particular flag is set and the user is prompted to define the frequency bandwidth of interest. This bandwidth must be within the previously defined start and stop frequencies and if it is not, the user is asked to redefine the bandwidth. Next the user is prompted to input the desired delta frequency and this value must be less than the defined bandwidth. Again, if it is not the user is asked to redefine the delta frequency. An intermediate value for the data point variable, N, is calculated and checked as to whether it is less than the maximum allowable value of 1024. If it is, a new value for N is calculated which satisfies the requirement for a 2^n point file necessary for fast Fourier transform. This value for N will be greater than the intermediate value and the process will yield a somewhat smaller delta frequency. The user is given the new values for the number of data points and the delta frequency. The program then returns to the end of the Measurement Setup Section. This method of data acquisition uses the default Sweep Mode of Continuous Sweep but the Sweep Type is changed from the default selection of Linear Frequency Sweep to Continuous Wave. This puts the HP 3577A in a single frequency measurement state. The display shows a single line from the bottom of the graticule to the height of the signal level at the specified frequency. The default Sample Time of 0.05 seconds is utilized [4]. Before measurement, the value of the minimum frequency is first stored for later plotting purposes. Measurement is taken via a FOR/NEXT loop and begins filling the arrays in either the first or second space depending upon the value of the Array Start Variable which depends upon the start frequency. The reason for this was previously explained in the Basic System Setup Section of this thesis. In the loop, the frequency of measurement is determined by an equation that will increment the frequency only after the first pass through the loop. The source frequency for the marker is set at this particular frequency and the number of digits are set to be accurate to one hertz. The Take Measurement and Dump Marker commands are executed and, as before, measurement is completed prior to data transfer. Dump Marker 1 dumps the value of the magnitude marker of Trace 1 in logarithmic form for the scattering parameters S_{21}, S_{12}, and S_{22}, and in linear form for the scattering parameter S_{11}. Dump Marker 2 dumps the value of the phase marker of Trace 2 in degrees for all the scattering parameters. These values are entered into two separate arrays and the program passes to the beginning of the loop. The frequency is incremented by the amount of the delta frequency to set a new source frequency for the marker and the measurements begin again. The number of passes through the loop is equal to the calculated number of data points, N, or to (N-1) depending on the Array Start Variable as previously described.

If the user chooses the data acquisition method by which the number of data points, N, is defined, that particular flag is set and the user is prompted to enter a value between, but not including, 1 and 1025. This value is given to the data point variable, N. The delta frequency is calculated and the program returns to the Measurement Setup Section. This method of data acquisition is identical to the previously described "Define the Delta Frequency" method except there is no option to save the results of measurement for future fast Fourier transform and arrays begin filling with data from the minimum frequency. The frequency is incremented at the end of the FOR/NEXT loop by simply adding the value for the delta frequency.

Device Testing

The quartz crystal devices tested were an intermediate frequency resonator, a high frequency resonator, and a surface acoustic wave filter. The resonators were obtained from the Electronics Industry Association of Olathe, Kansas, and are referred to as device J69 for the IF resonator and device F83 for the HF resonator. The SAW filter was built at the University of Central Florida, and is referred to as the SAW filter.

All measurements for device J69 were made with a start frequency of 3.5782215 MHz and stop frequency of 3.5792215 MHz, thus giving a frequency span of 1 kHz with the center frequency at resonance, 3.5787215 MHz. All measurements for device F83 were made with a start frequency of 40.67869 MHz and a stop frequency of 40.68869 MHz, thus giving a frequency span of 10 kHz with the center frequency at resonance, 40.683690 MHz. The drive level for each of the three devices was 0 dBm.

The scattering parameter S_{21} was measured from device F83 three times using each of the data acquisition methods for comparison purposes. Figures 2 and 3 show the magnitude and phase plots made using the "Dump the Screen" method. Here, 401 data points were measured over the bandwidth of 10 kHz and the delta frequency between points was 25 Hz. Figures 4 and 5 show the magnitude and phase plots made using the "Define the Number of Data Points" method. This number, N, was chosen to be 401 in order to compare the plots more closely with the "Dump the Screen" method. As before, the delta frequency between points was 25 Hz. Figures 6 and 7 show the magnitude and phase plots made using the "Define the Delta Frequency" method. Since the number of data points will be in the form $N=2^n$, a delta frequency was chosen which would prompt the program to calculate a value of N closest to 401 for comparison purposes. This value was N=512 with a delta frequency of 19.53125 Hz. Error runs were also made with the above three data acquisition methods. Plots of the magnitude and phase errors are to follow. The device F83 was then normalized for S_{21} from the front panel of the network analyzer without the use of the computer program. The number of data points is 401 and the delta frequency between these points is 25 Hz. The plot of magnitude and phase is shown in Figure 8. Good correlation between all methods is observed.

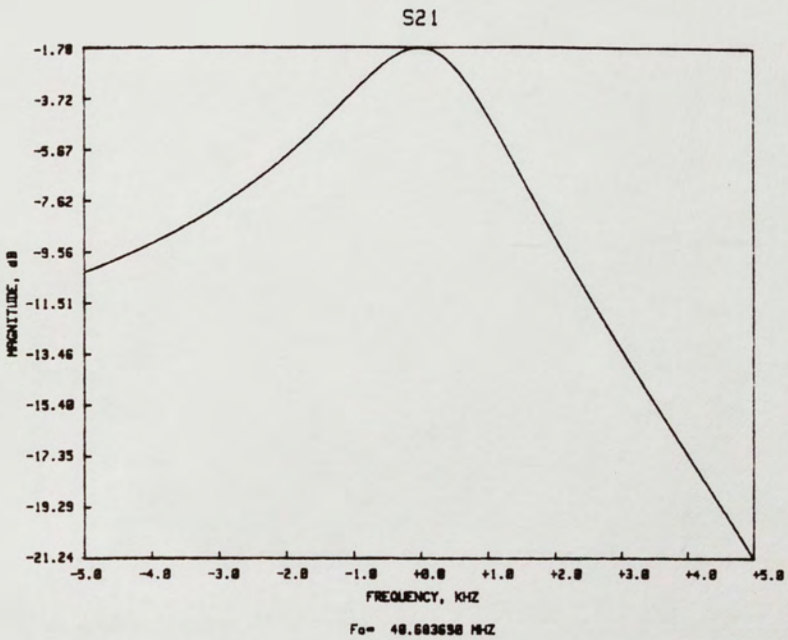

Figure 2. S_{21} Magnitude Plot of Device F83 Using the "Dump the Screen" Data Acquisition Method

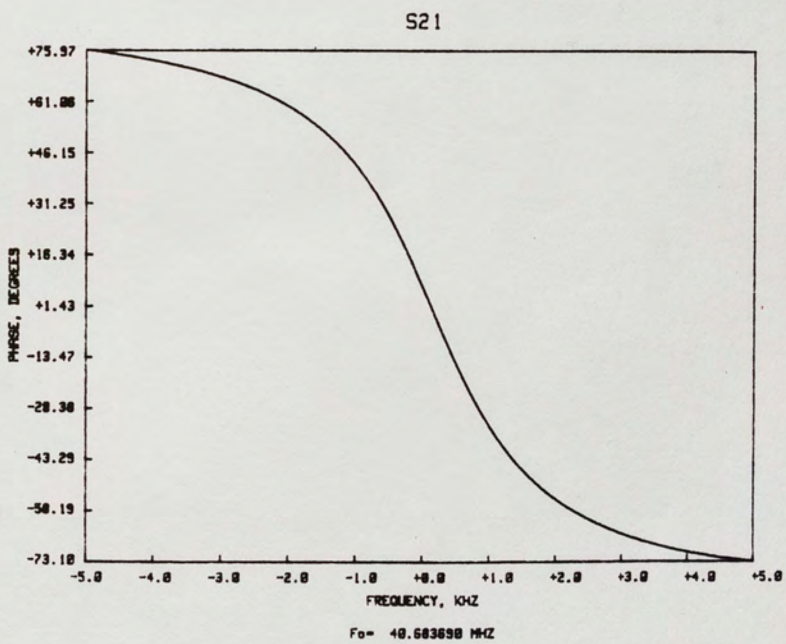

Figure 3. S_{21} Phase Plot of Device F83 Using the "Dump the Screen" Data Acquisition Method

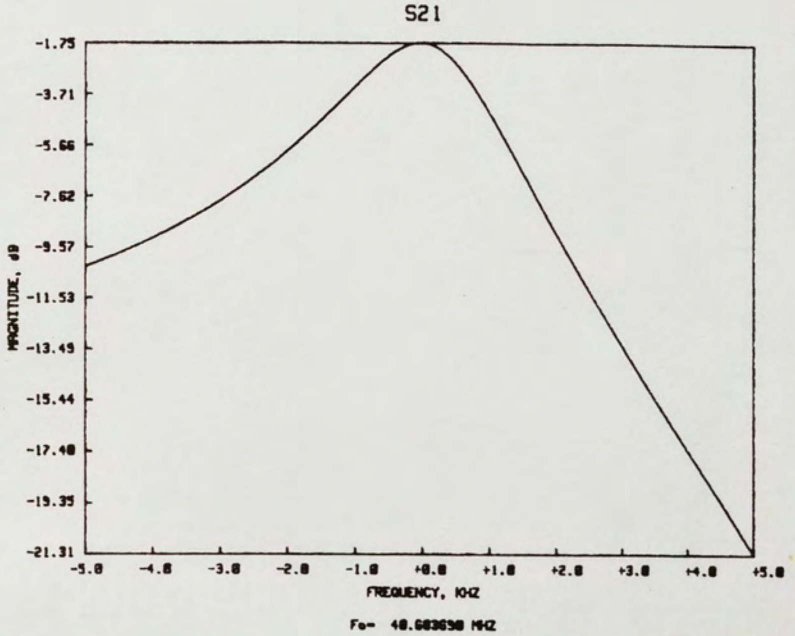

Figure 4. S_{21} Magnitude Plot of Deice F83 Using the "Define the Number of Data Points" Data Acquisition Method

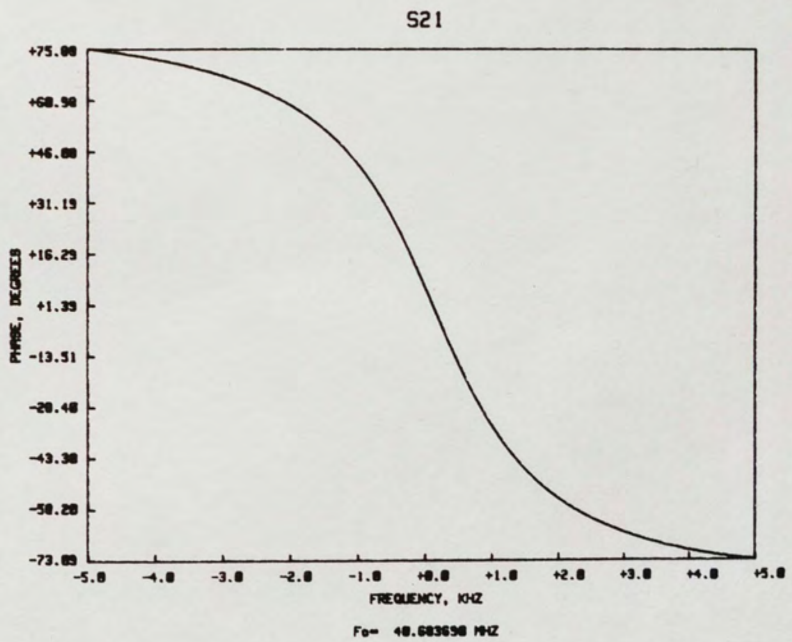

Figure 5. S_{21} Phase Plot of Device F83 Using the "Define the Number of Data Points" Data Acquisition Method

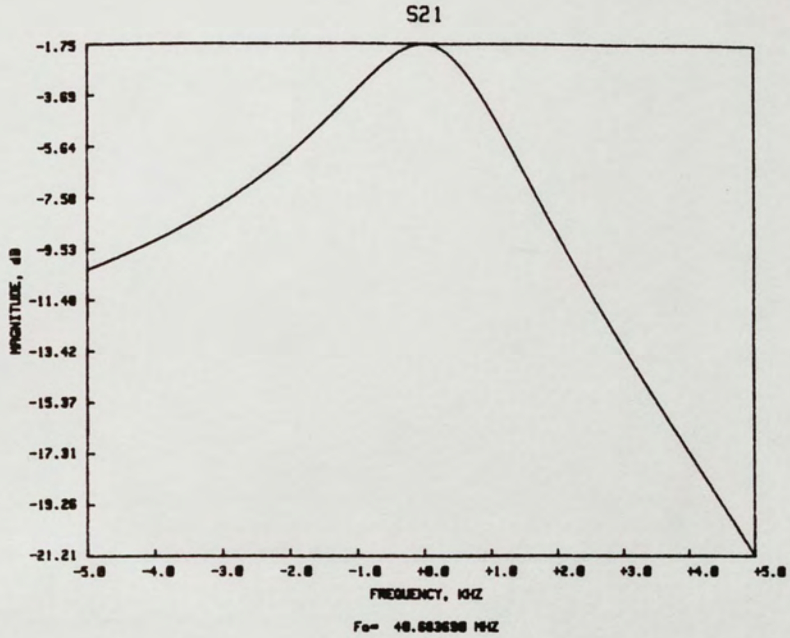

Figure 6. S_{21} Magnitude Plot of Deice F83 Using the "Define the Delta Frequency" Data Acquisition Method

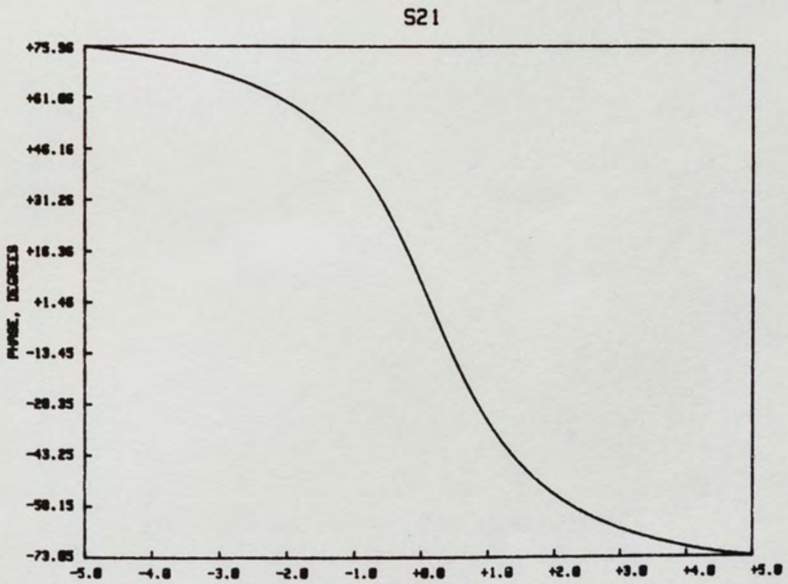

Figure 7. S_{21} Phase Plot of Device F83 Using the "Define the Delta Frequency" Data Acquisition Method

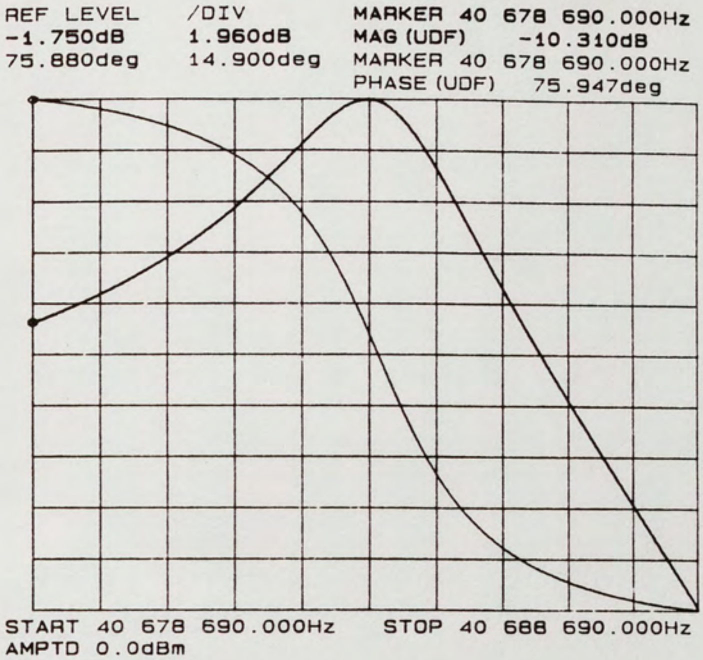

Figure 8. S_{21} Magnitude and Phase Plot of Device F83 Made Directly from the HP 3577A Network Analyzer

If the "Dump the Screen" method is used as a standard for comparison, then the percent difference in the plots can be calculated using the equation

$$\frac{(\text{Expected Value} - \text{Measured Value})}{\text{Expected Value}} \times 100\% \quad .$$

Adjusting for logarithmic form, the percent difference in magnitude at resonance is

$$\frac{\left(10^{\frac{-1.78}{20}} - 10^{\frac{-1.75}{20}}\right)}{10^{\frac{-1.78}{20}}} \times 100\% = -0.35\%$$

for both the "Define the Number of Data Points" and the "Define the Delta Frequency" methods. The percent difference in the amplitude range can be calculated between the "Dump the Screen" and "Define the Number of Data Points" methods by

$$\frac{\left(10^{\frac{-1.78}{20}}-10^{\frac{-21.24}{20}}\right)-\left(10^{\frac{-1.75}{20}}-10^{\frac{-21.31}{20}}\right)}{\left(10^{\frac{-1.78}{20}}-10^{\frac{-21.24}{20}}\right)}\times 100\% = -0.48\%$$

where, as before, adjustment is made for logarithmic form.

By similar calculations, the percent difference in the amplitude range between the "Dump the Screen" and "Define the Delta Frequency" methods is -0.35%. The percent difference in the phase at resonance between the "Dump the Screen" and "Define the Number of Data Points" methods is found to be

$$\frac{(1.43-1.39)}{1.43}\times 100\% = 2.8\% \ .$$

The percent difference in the phase at resonance between the "Dump the Screen" and "Define the Delta Frequency" methods is 2.1%. Between the "Dump the Screen" and "Define the Number of Data Points" methods, the percent difference in phase range is

$$\frac{((75.97-(-73.1))-(75.88-(-73.09)))}{(75.97-(-73.1))}\times 100\% = 0.067\% \ .$$

Similarly, the percent difference in phase range between the "Dump the Screen" and "Define the Delta Frequency" is 0.04%. These values of percent differences can be found in Table 2. The plot of magnitude and phase of S_{21} made from the front panel is seen to have similar characteristics as the six plots using the computer program's data acquisition.

The scattering parameter S_{12} was measured for devices F83 and J69, twice each, for the purpose of comparing two error runs. The "Define the Delta Frequency" method of data acquisition was chosen. The delta frequency for device F83 was 19.53125 Hz with N=512 points. Figures 9 through 12 show the magnitude and phase plots of the first and second run. Figure 13 shows the normalized magnitude and phase plot made from the front panel of the network analyzer without the use of the computer program. The delta frequency is 25 Hz and N=401 points as before. If a comparison of runs is made using the first run as the standard, the percent difference in magnitude at resonance is 0.12% and the percent difference in amplitude range is 0.15%. Calculations were similar to those used previously. The percent difference in phase at resonance is -4.2% and the percent difference in the phase range is 0.13%. These values are repeated in Table 2. The plot of magnitude and phase made from the front panel of the network analyzer is seen to have similar characteristics as the four plots using

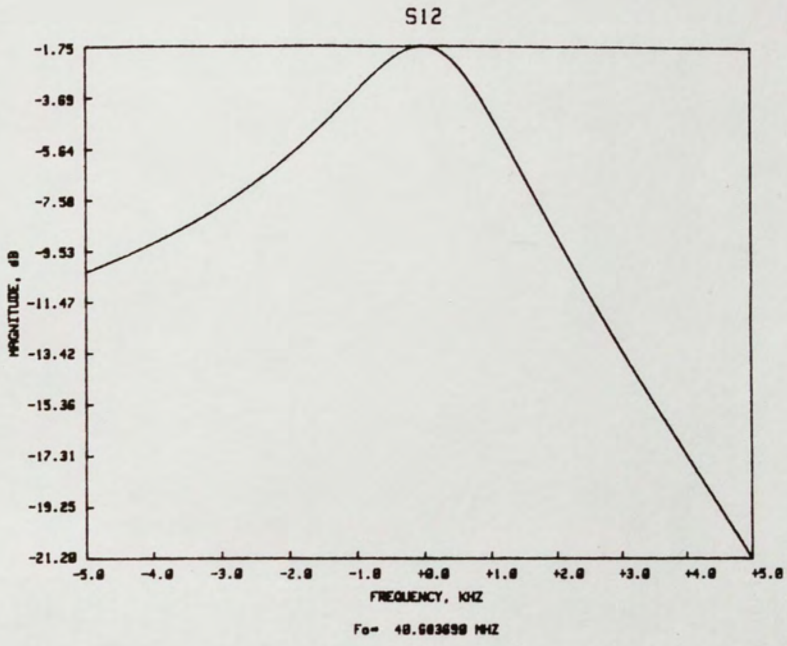

Figure 9. S_{12} Magnitude Plot of Device F83; First Run

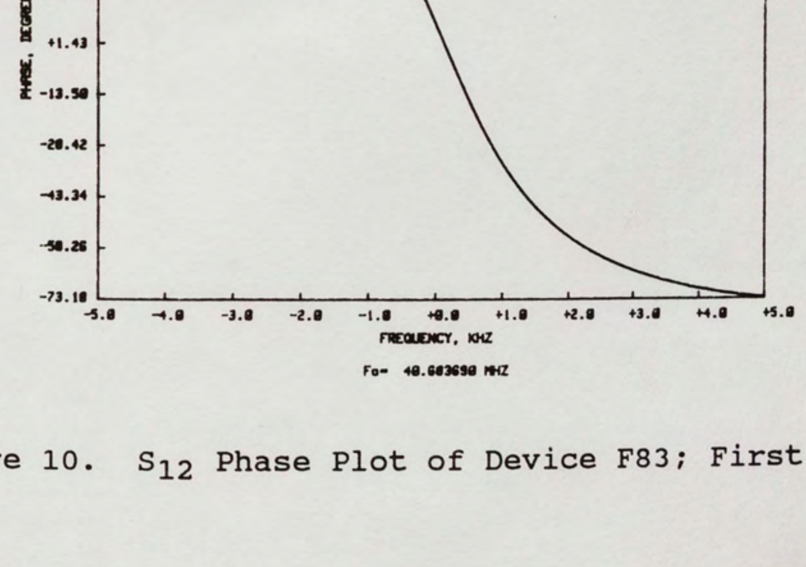

Figure 10. S_{12} Phase Plot of Device F83; First Run

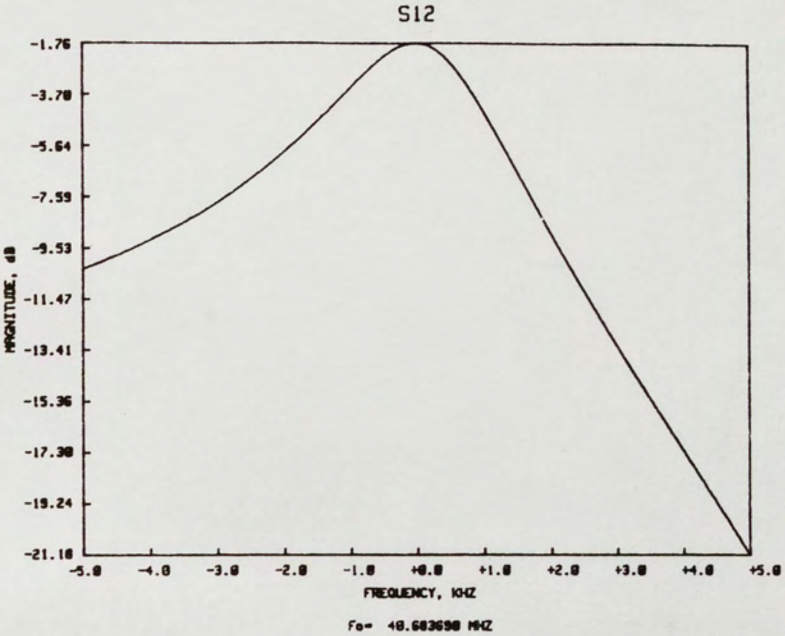

Figure 11. S_{12} Magnitude Plot of Device F83; Second Run

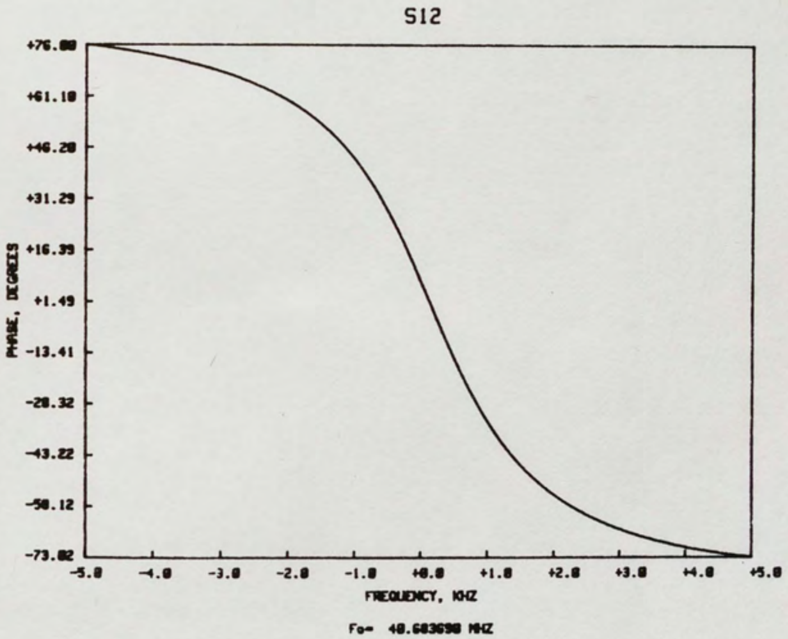

Figure 12. S_{12} Phase Plot of Device F83; Second Run

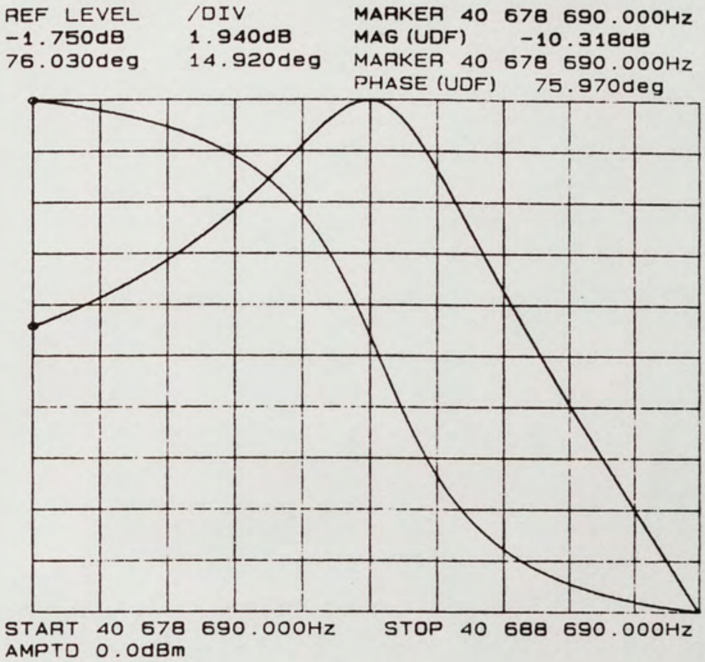

Figure 13. S_{12} Magnitude and Phase Plot of Device F83 Made Directly from the HP 3577A Network Analyzer

the computer program's data acquisition. Figures 14 through 17 show the magnitude and phase plots of the first and second run from device J69. The delta frequency was 1.953125 Hz with N=512 points. Figure 18 shows the normalized magnitude and phase plot for the device made from the front panel of the network analyzer. The delta frequency is 2.5 Hz with N=401 points. If a comparison of runs is made using the first run as the standard, the percent difference in magnitude at resonance is -0.12% and the percent difference in amplitude range is -0.12%.

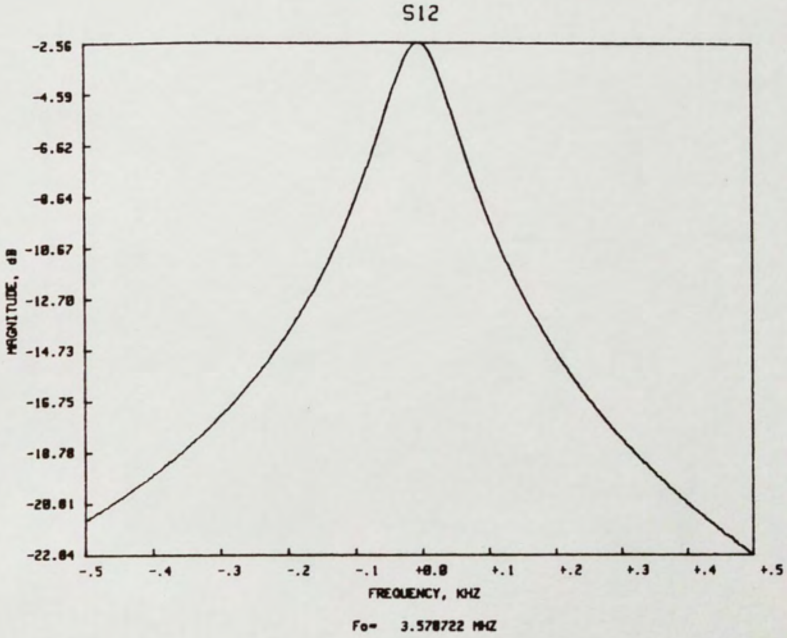

Figure 14. S_{12} Magnitude Plot of Device J69; First Run

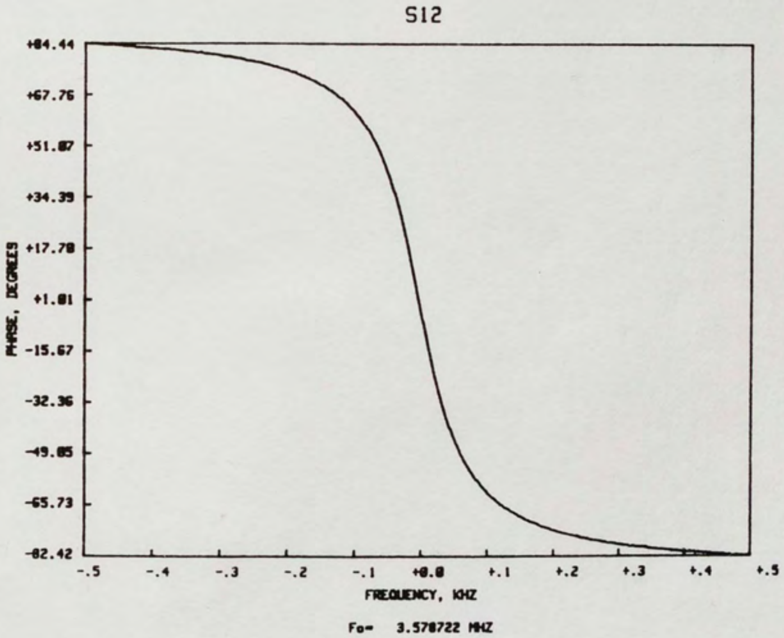

Figure 15. S_{12} Phase Plot of Device J69; First Run

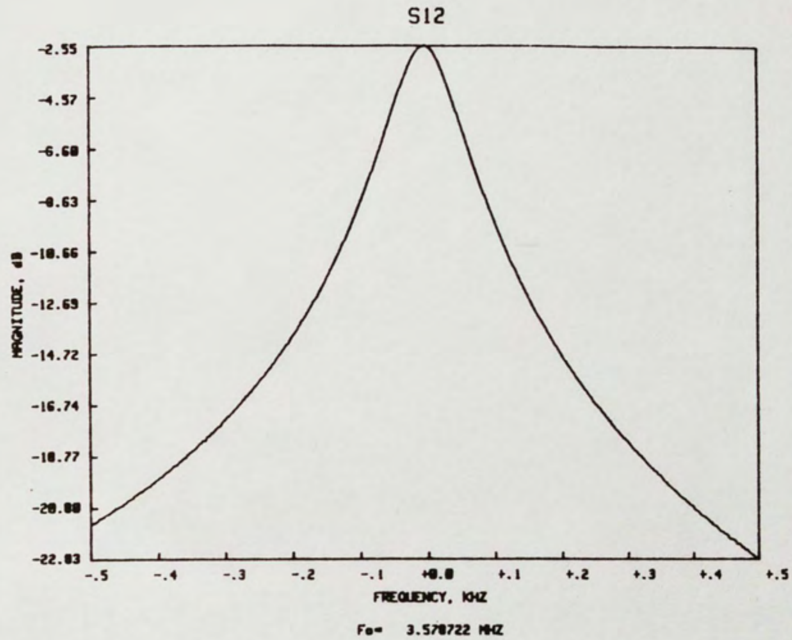

Figure 16. S_{12} Magnitude Plot of Device J69; Second Run

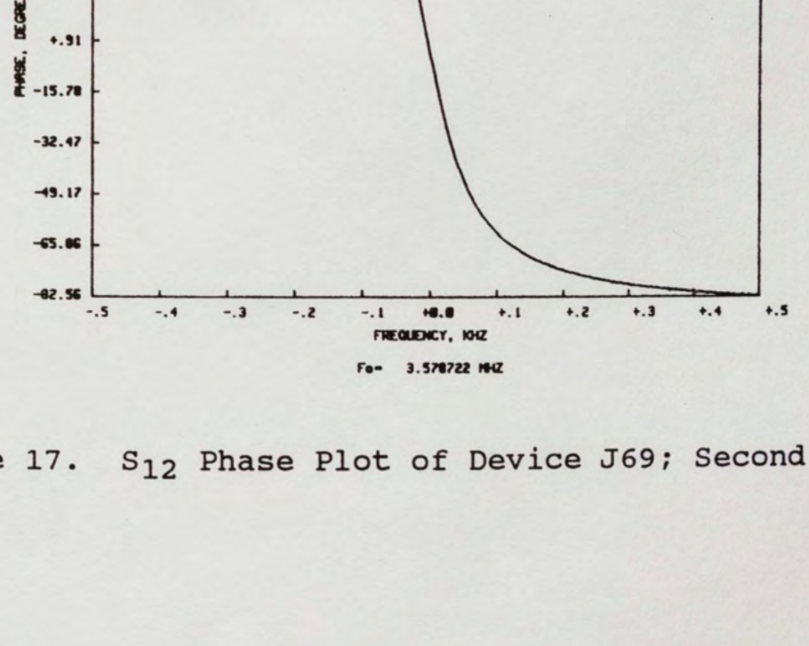

Figure 17. S_{12} Phase Plot of Device J69; Second Run

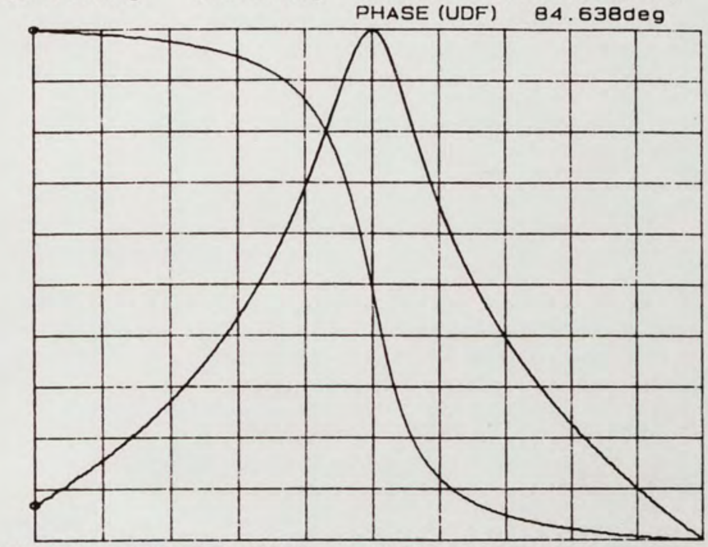

Figure 18. S_{12} Magnitude and Phase Plot of Device J69 Made Directly from the HP 3577A Network Analyzer

The percent difference in phase at resonance is 9.9% and the percent difference in phase range is -0.048%. Again, these results can be found in Table 2. The error run plots for both of these devices are to follow.

The scattering parameter S_{11} was measured from devices F83 and J69 twice each also for the purpose of comparing two error runs. The "Define the Delta Frequency" method of data acquisition was again chosen and the values for the delta frequency and number of data points are as before. Figures 19 through 22 show the magnitude and phase plots of the first and second run from device F83.

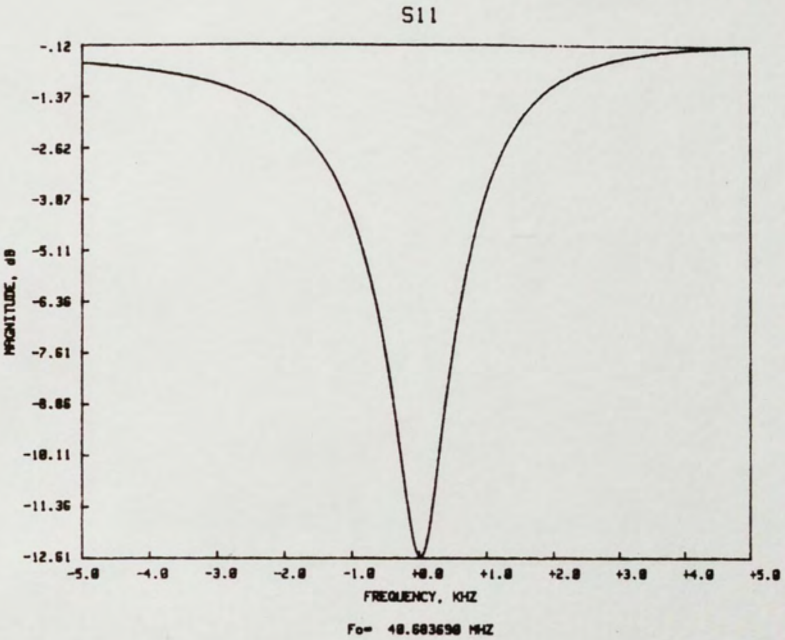

Figure 19. S_{11} Magnitude Plot of Device F83; First Run

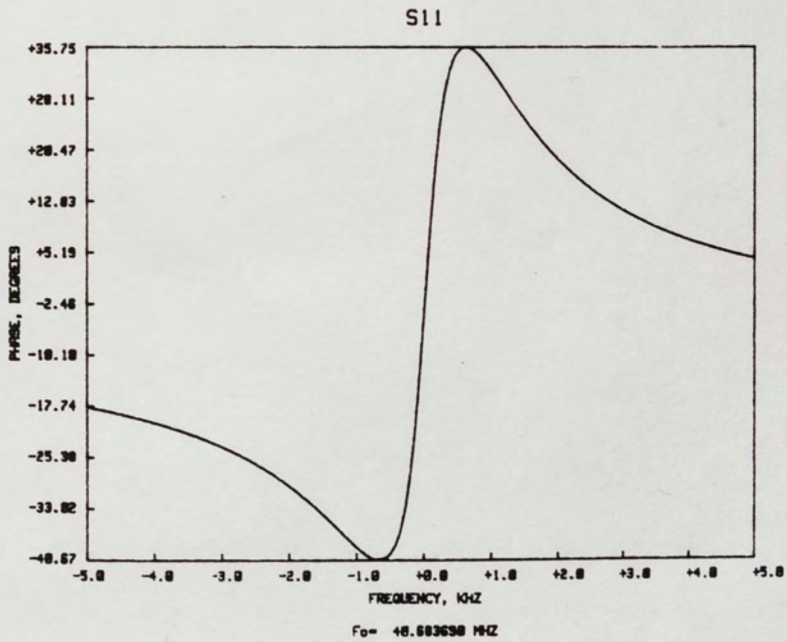

Figure 20. S_{11} Phase Plot of Device F83; First Run

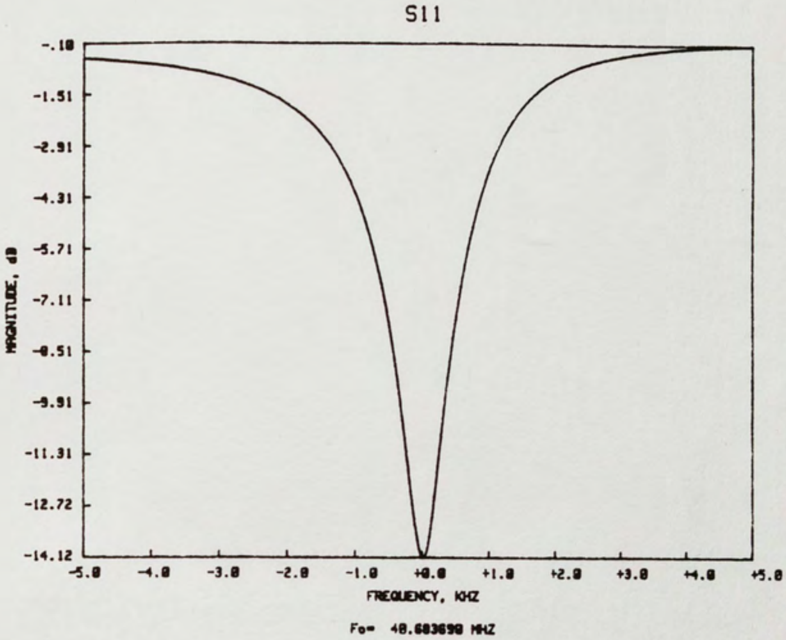

Figure 21. S_{11} Magnitude Plot of Device F83; Second Run

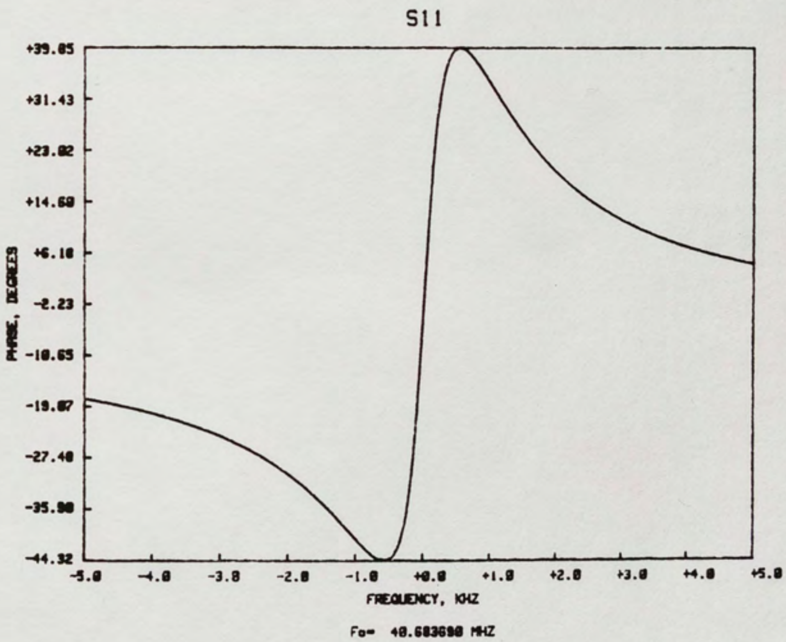

Figure 22. S_{11} Phase Plot of Device F83; Second Run

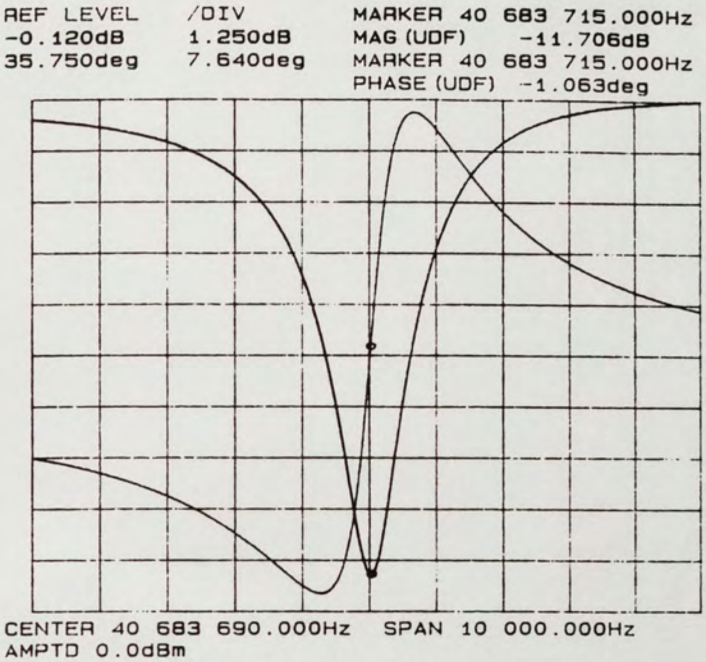

Figure 23. S_{11} Magnitude and Phase Plot of Device F83 Made Directly from the HP 3577A Network Analyzer

Figure 23 shows the calibrated magnitude and phase plot made from the front panel of the network analyzer. Comparison of runs show a percent difference in magnitude at resonance of 15.96%, a percent difference in amplitude range of -5.28%, a percent difference in phase at resonance of 9.35%, and a percent difference in phase range of -10.1%. Figures 24 through 27 show the magnitude and phase plots of the first and second run from device J69. Figure 28 shows the calibrated magnitude and phase plot made from the front panel of the network analyzer.

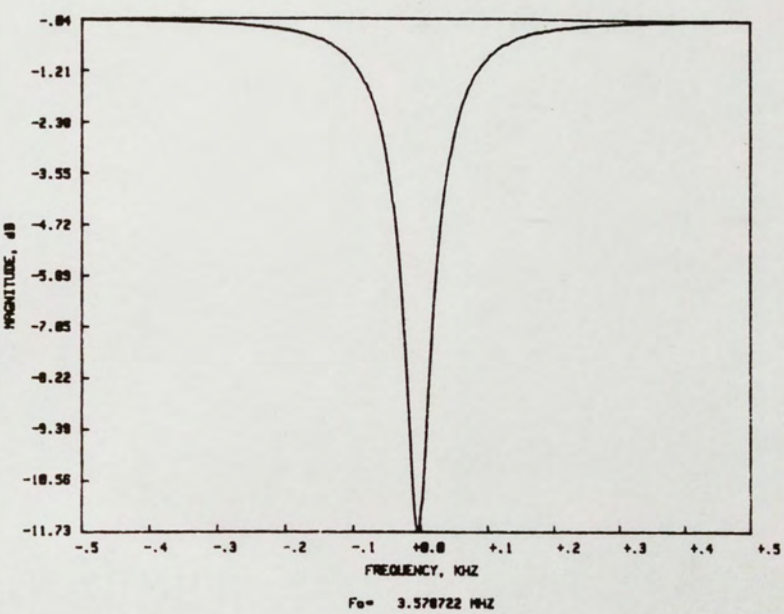

Figure 24. S_{11} Magnitude Plot of Device J69; First Run

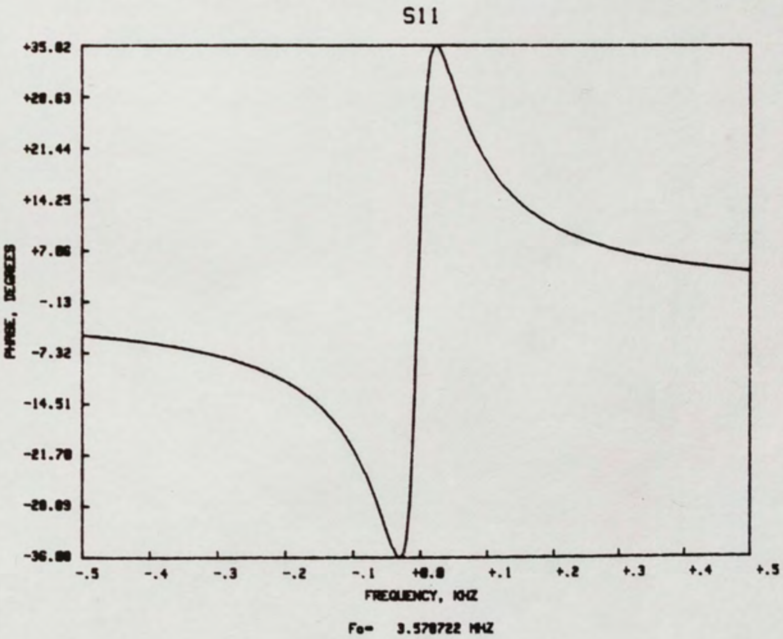

Figure 25. S_{11} Phase Plot of Device J69; First Run

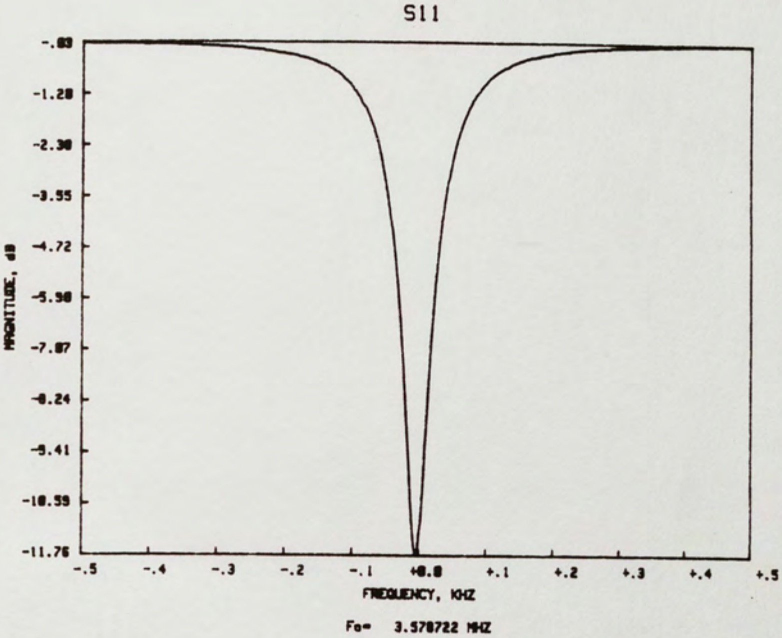

Figure 26. S_{11} Magnitude Plot of Device J69; Second Run

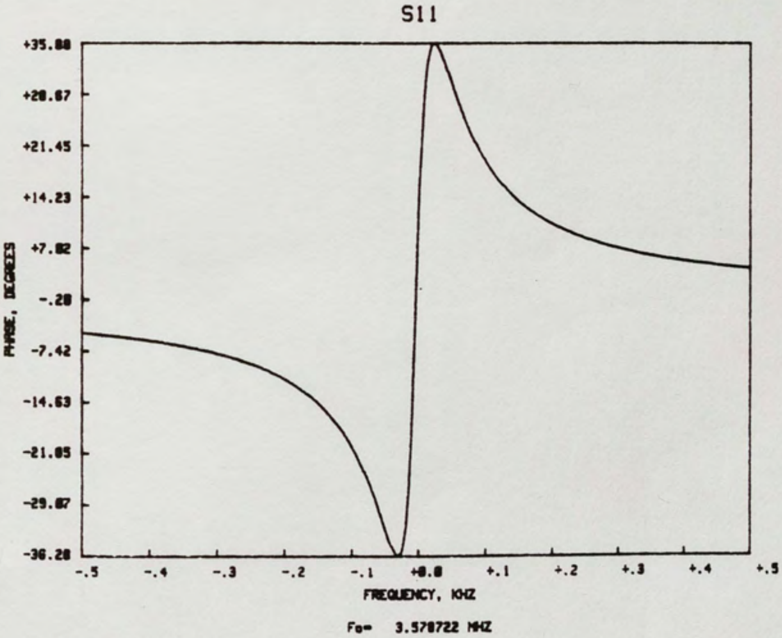

Figure 27. S_{11} Phase Plot of Device J69; Second Run

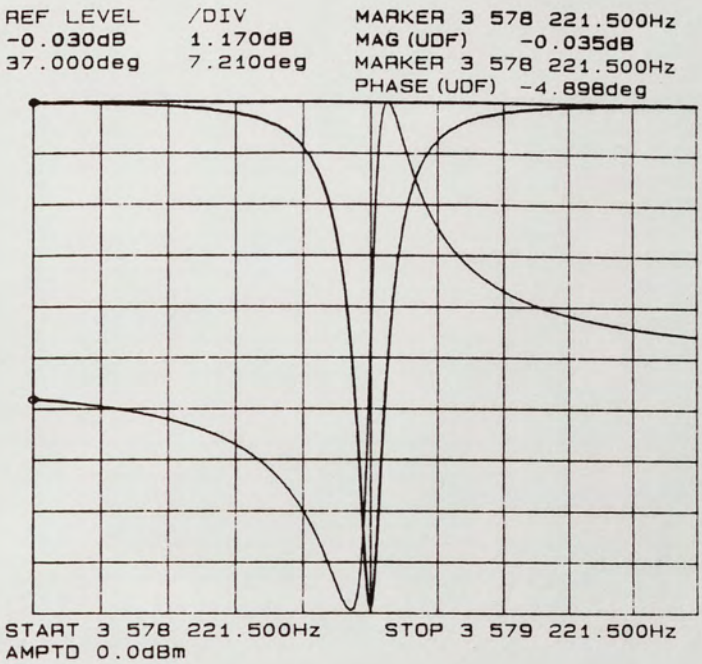

Figure 28. S_{11} Magnitude and Phase Plot of Device J69 Made Directly from the HP 3577A Network Analyzer

A comparison of runs show a percent difference in magnitude at resonance of 0.34%, a percent difference in amplitude range of -0.27%, a percent difference in phase at resonance of -53.8%, and a percent difference in phase range of 0.36%. The error run plots for both of these devices are to follow.

The scattering parameter S_{22} was measured twice from device J69. The "Define the Number of Data Points" method of data acquisition was chosen. Figures 29 and 30 show the magnitude and phase plots of the measurements using N=401 and figures 31 and 32 show the plots of the measurements using N=1024.

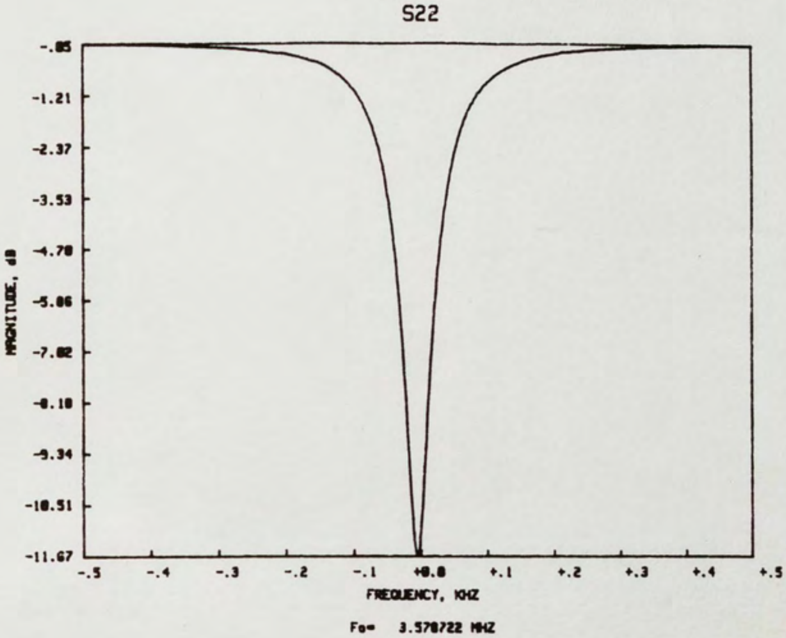

Figure 29. S_{22} Magnitude Plot of Device J69 with N=401

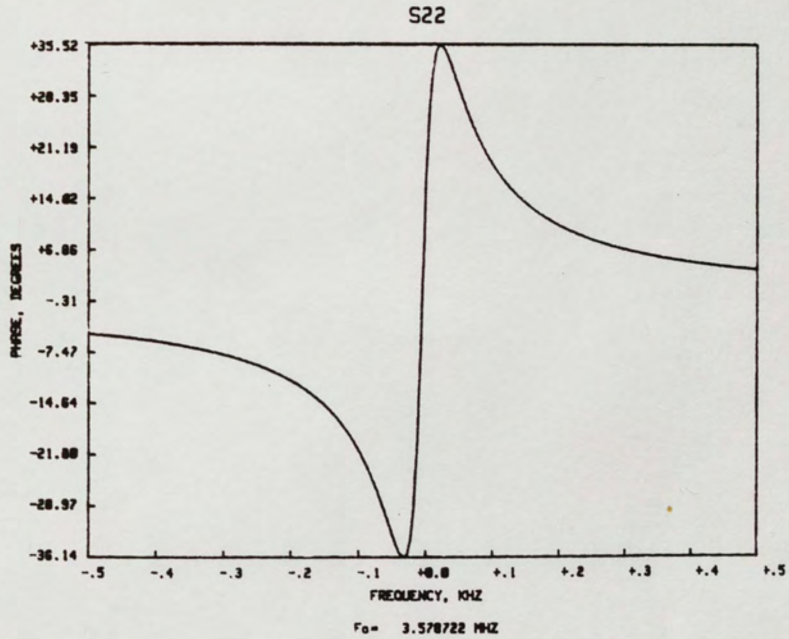

Figure 30. S_{22} Phase Plot of Device J69 with N=401

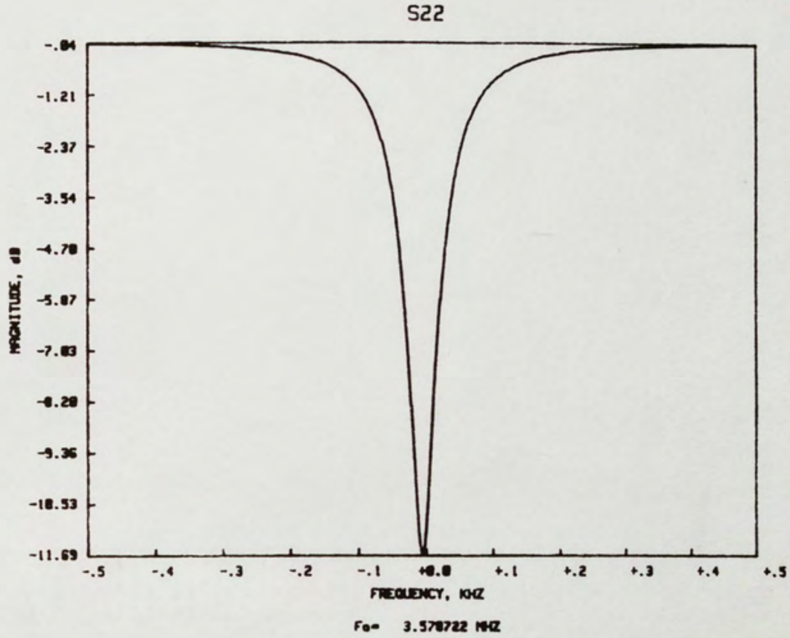

Figure 31. S_{22} Magnitude Plot of Device J69 with N=1024

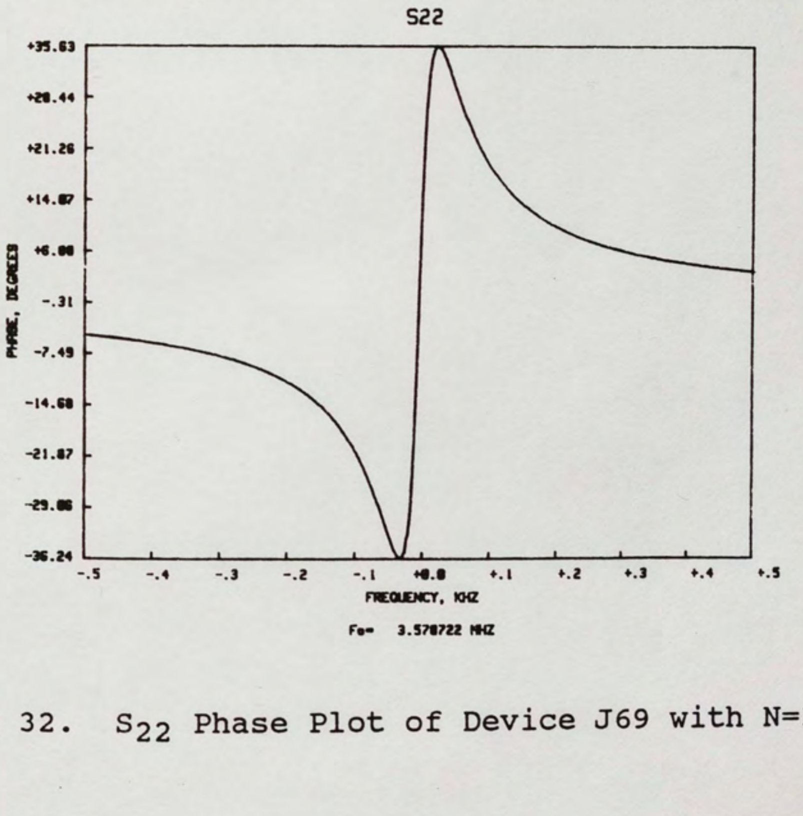

Figure 32. S_{22} Phase Plot of Device J69 with N=1024

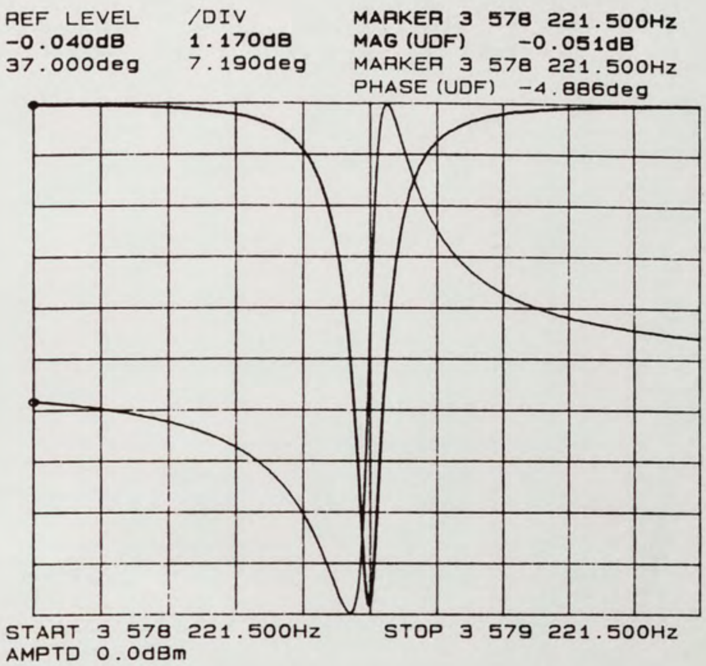

Figure 33. S_{22} Magnitude and Phase Plot of Device J69 Made Directly from the HP 3577A Network Analyzer

Figure 33 shows the normalized magnitude and phase plot made from the front panel of the network analyzer. A comparison of measurements taken with different number of data points show a percent difference in magnitude at resonance of 0.23%, a percent difference in amplitude range of -0.25%, a percent difference in phase at resonance of 0.0%, and a percent difference in phase range of -0.29%. These values, as before, are repeated in Table 2. The purpose for making these measurements is to compare the error runs. Plots of those runs are to follow.

The scattering parameter S_{21} was also measured from the SAW device. The start frequency was 0 Hz and the stop frequency was 90 MHz. The "Define the Delta Frequency" method of data acquisition was used with Df=0.17578125 and N=512. Actual data acquisition began at 0.17578125 MHz for reasons previously explained in the Data Acquisition Methods section of this thesis. Figures 34 and 35 show the magnitude and phase plots. Figures 36 and 37 show the normalized magnitude and phase plots made from the front panel of the network analyzer. As before, N=401 and so the delta frequency between data points was 0.225 MHz. This set of plots can be seen to have similar characteristics as the set of plots made using the computer program. The results of the magnitude measurements were saved on the hard disc and another computer program was utilized to find the fast Fourier transform of the data. Figure 38 shows the plot of the transform. Note that the plot now shows magnitude versus time.

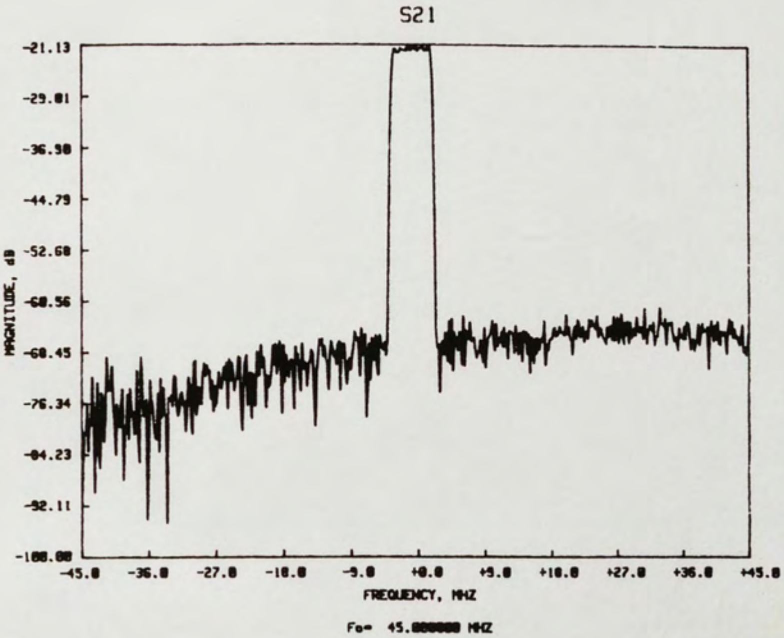

Figure 34. S_{21} Magnitude Plot of SAW Device

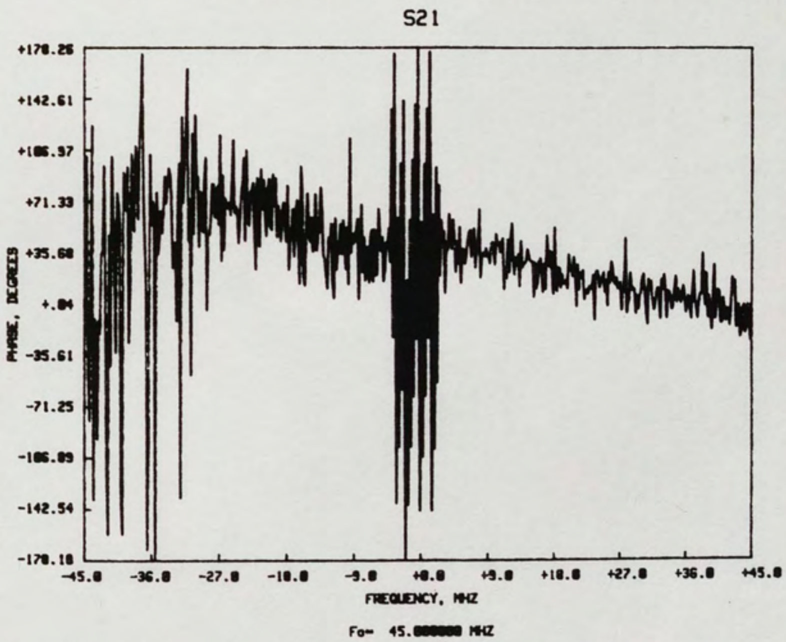

Figure 35. S_{21} Phase Plot of SAW Device

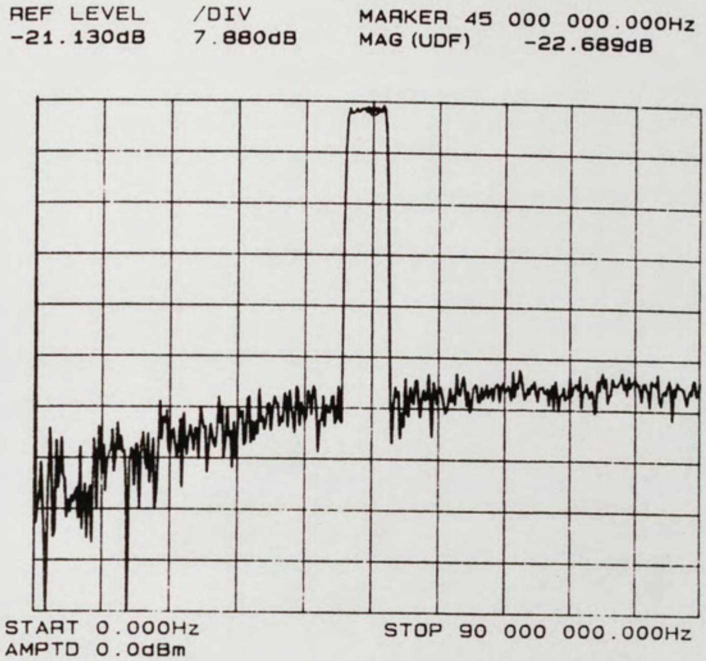

Figure 36. S_{21} Magnitude Plot of SAW Device Made Directly from the HP 3577A Network Analyzer

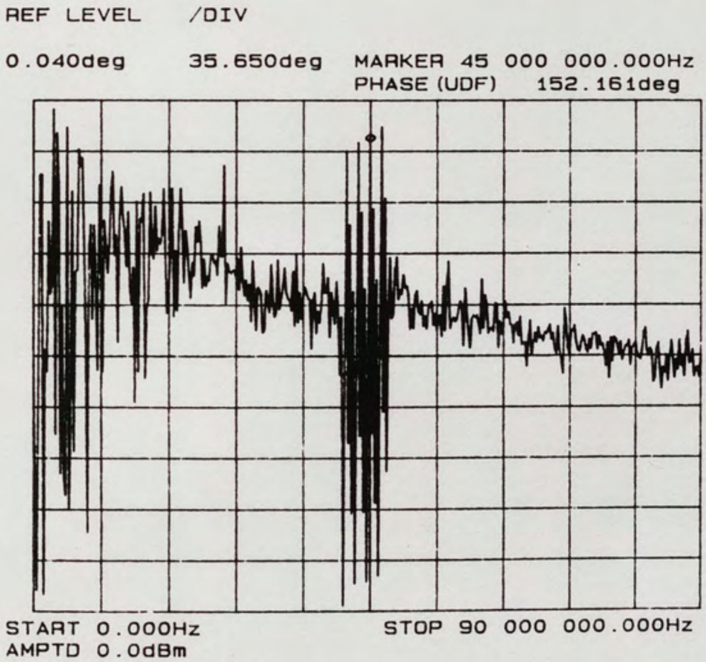

Figure 37. S_{21} Phase Plot of SAW Device Made Directly from the HP 3577A Network Analyzer

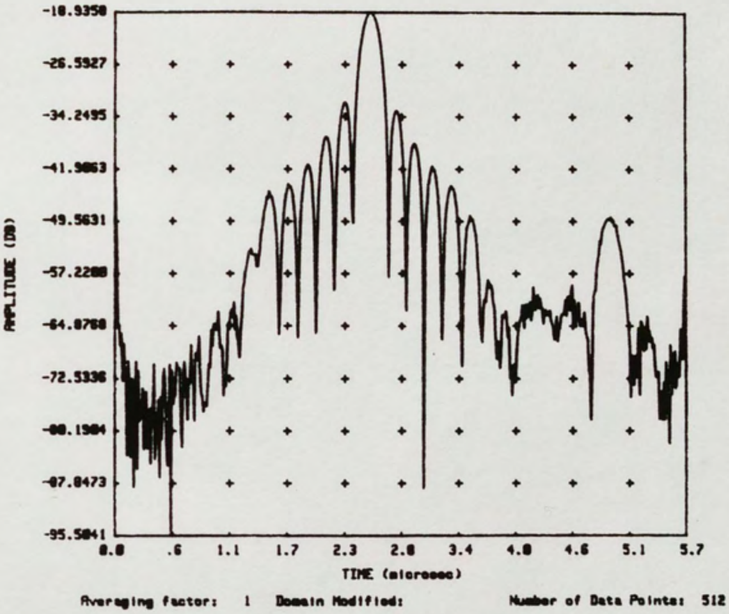

Figure 38. Fast Fourier Transform of the S_{21} Measurement from the SAW Device

TABLE 2

MEASUREMENT COMPARISONS

Device	Methods Compared	Measurement Compared	Percent Difference
1. F83	Dump the Screen Define N	Magnitude at Resonance	-0.35%
2. F83	Dump the Screen Define Df	Magnitude at Resonance	-0.35%
3. F83	Dump the Screen Define N	Magnitude Range	-0.48%
4. F83	Dump the Screen Define Df	Magnitude Range	-0.35%
5. F83	Dump the Screen Define N	Phase at Resonance	2.8%
6. F83	Dump the Screen Define Df	Phase at Resonance	2.1%
7. F83	Dump the Screen Define N	Phase Range	0.067%
8. F83	Dump the Screen Define Df	Phase Range	0.04%
9. F83	Define Df; First Run Define Df; Second Run	Magnitude at Resonance	0.12%
10. F83	Define Df; First Run Define Df; Second Run	Magnitude Range	0.15%
11. F83	Define Df; First Run Define Df; Second Run	Phase at Resonance	-4.2%
12. F83	Define Df; First Run Define Df; Second Run	Phase Range	0.13%
13. J69	Define Df; First Run Define Df; Second Run	Magnitude at Resonance	-0.12%
14. J69	Define Df; First Run Define Df; Second Run	Magnitude Range	-0.12%
15. J69	Define Df; First Run Define Df; Second Run	Phase at Resonance	9.9%
16. J69	Define Df; First Run Define Df; Second Run	Phase Range	-0.048%
17. F83	Define Df; First Run Define Df; Second Run	Magnitude at Resonance	15.96%
18. F83	Define Df; First Run Define Df; Second Run	Magnitude Range	-5.28%
19. F83	Define Df; First Run Define Df; Second Run	Phase at Resonance	9.35%
20. F83	Define Df; First Run Define Df; Second Run	Phase Range	-10.1%
21. J69	Define Df; First Run Define Df; Second Run	Magnitude at Resonance	0.34%
22. J69	Define Df; First Run Define Df; Second Run	Magnitude Range	-0.27%
23. J69	Define Df; First Run Define Df; Second Run	Phase at Resonance	-53.8%
24. J69	Define Df; First Run Define Df; Second Run	Phase Range	0.36%
25. J69	Define N=401 Define N=1024	Magnitude at Resonance	0.23%
26. J69	Define N=401 Define N=1024	Magnitude Range	-0.25%
27. J69	Define N=401 Define N=1024	Phase at Resonance	0.0%
28. J69	Define N=401 Define N=1024	Phase Range	-0.29%

Error Analysis

Figure 39 shows the plot of the S_{21} magnitude error of device F83 using the "Dump the Screen" method. The error range is approximately +/- 0.03 dB. Figure 40 shows the plot of the S_{21} phase error of device F83 using the "Dump the Screen" method. The error ranges from -0.11 degrees to +0.19 degrees with the increases noted slightly above resonant frequency where the phase change is great over a small frequency range, and at higher frequencies where the phase just begins to approach -90 degrees (see Figure 3). Figure 41 shows the plot of the S_{21} magnitude error of device F83 using the "Define the Number of Data Points" method. The error range is approximately +/- 0.02 dB across the majority of the frequency span. At higher frequencies when the magnitude decreases (see Figure 4), the error ranges from -0.02 dB to +0.03 dB. Figure 42 shows the plot of the S_{21} phase error of device F83 using the "Define the Number of Data Points" method. The error ranges from -0.09 degrees to +0.3 degrees with the increase noted at higher frequencies where the phase just begins to approach -90 degrees (see Figure 5). Figure 43 shows the plot of the S_{21} magnitude error of device F83 using the "Define the Delta Frequency" method. The error ranges from -0.05 dB to +0.03 dB with the increase noted at higher frequencies when the magnitude decreases (see Figure 6).

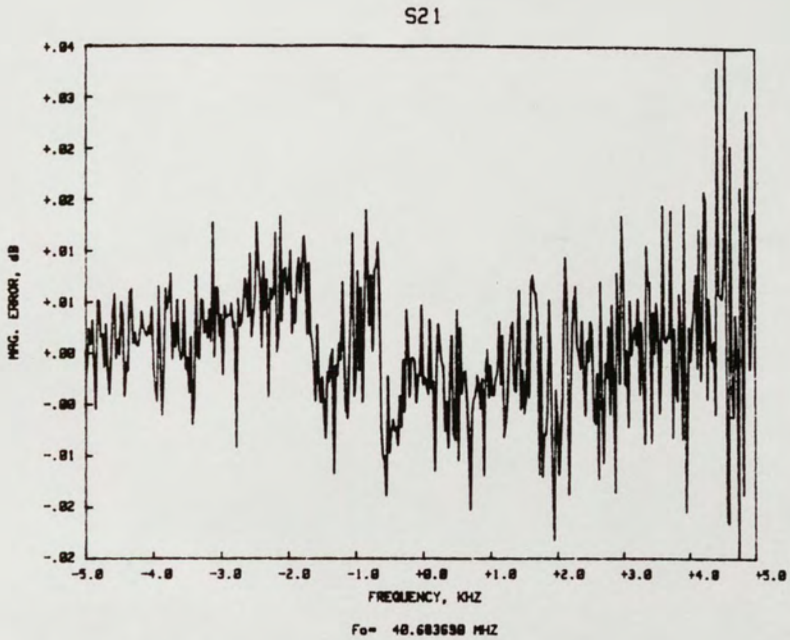

Figure 39. S_{21} Magnitude Error Plot of Device F83 Using the "Dump the Screen" Data Acquisition Method

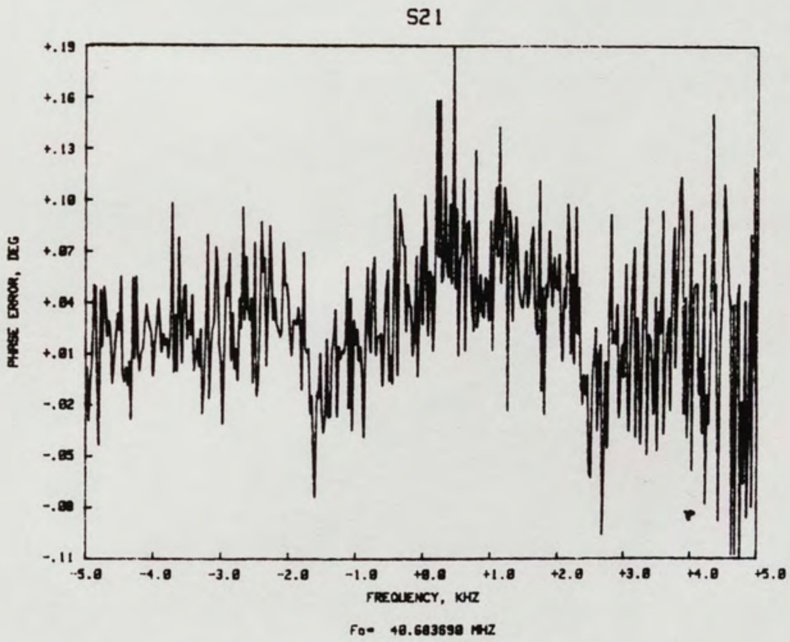

Figure 40. S_{21} Phase Error Plot of Device F83 Using the "Dump the Screen" Data Acquisition Method

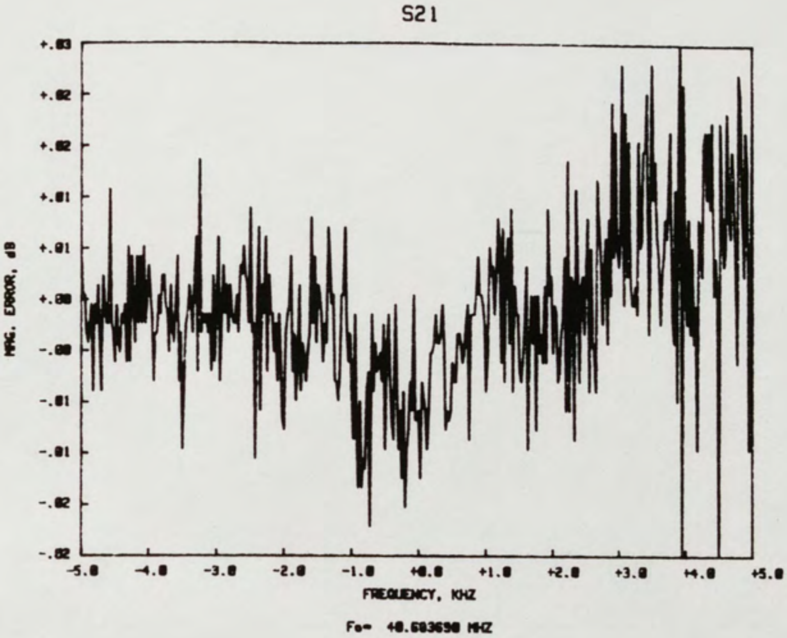

Figure 41. S_{21} Magnitude Error Plot of Device F83 Using the "Define the Number of Data Points" Data Acquisition Method

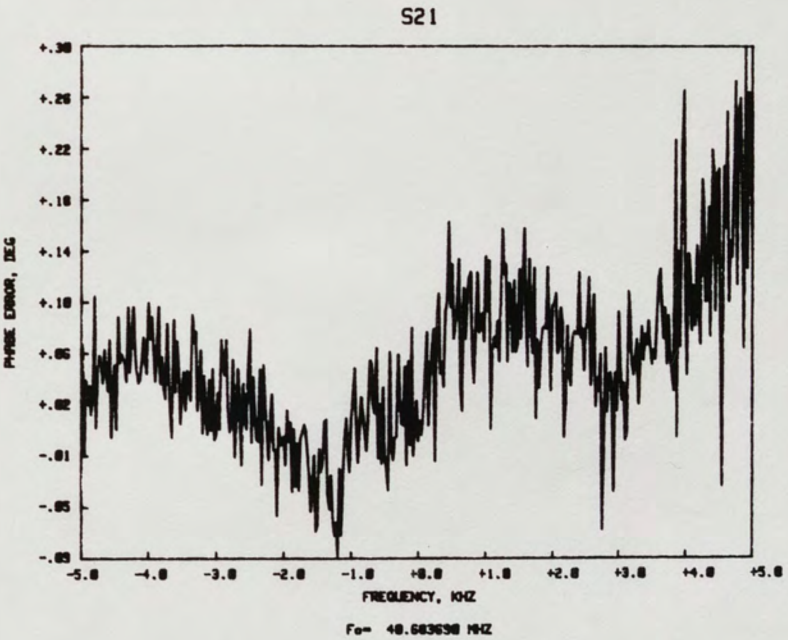

Figure 42. S_{21} Phase Error Plot of Device F83 Using the "Define the Number of Data Points" Data Acquisition Method

Figure 44 shows the S_{21} phase error plot of device F83 using the "Define the Delta Frequency" method. The error ranges from -0.10 degrees to +0.20 degrees with the increase noted at higher frequencies where the phase just begins to approach -90 degrees (see Figure 7). Table 3 shows the maximum errors for each measurement.

Figures 45 and 46 show the S_{12} magnitude error plots of device F83 for the first and second run. The first run error ranges from -0.03 dB to +0.02 dB and the second run error ranges from -0.02 dB to +0.03 dB. The increased errors are noted at higher frequencies where the S_{12} magnitude decreases (see figures 9 and 11). Figures 47 and 48 show the S_{12} phase error plots of device F83 for the first and second run. The first run error ranges form -0.15 degrees to +0.18 degrees with the maximum error occurring slightly beyond the resonant frequency where the change in phase is great over a small frequency span (see Figure 10). The second run error ranges from -0.20 degrees to +0.23 degrees with the increase noted at higher frequencies where the phase just begins to approach -90 degrees (see Figure 12).

Figures 49 and 50 show the S_{12} magnitude error plots of device J69 for the first and second run. The first run error ranges from -0.08 dB to +0.08 dB and the second run error ranges from -0.07 dB to +0.09 dB.

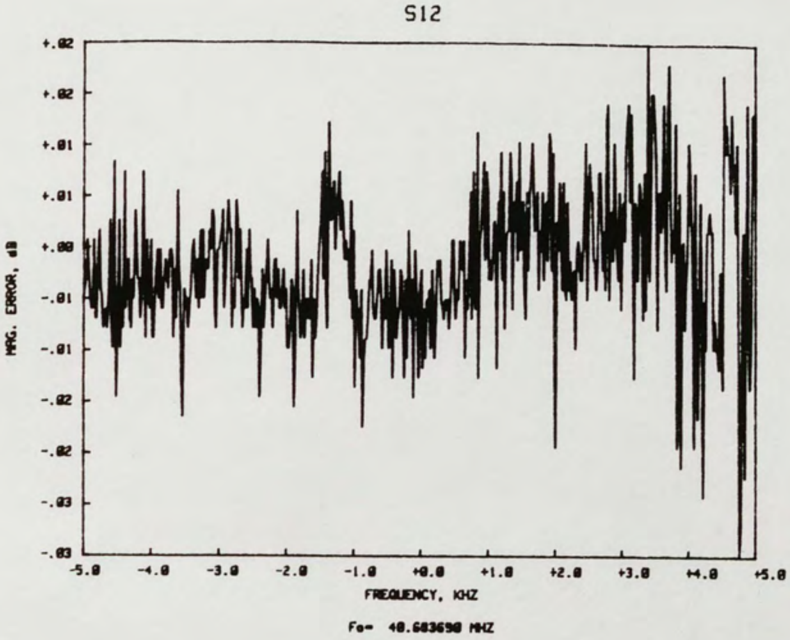

Figure 45. S_{12} Magnitude Error Plot of Device F83; First Run

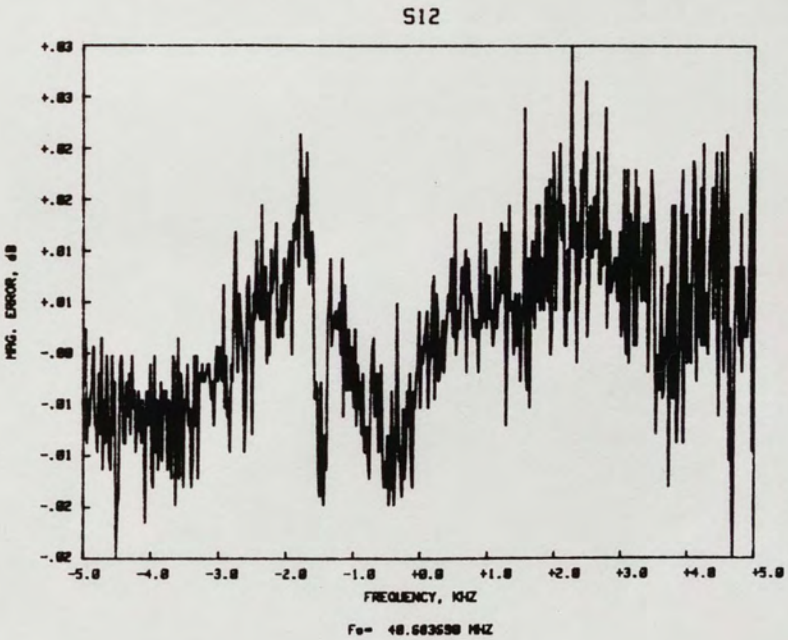

Figure 46. S_{12} Magnitude Error Plot of Device F83; Second Run

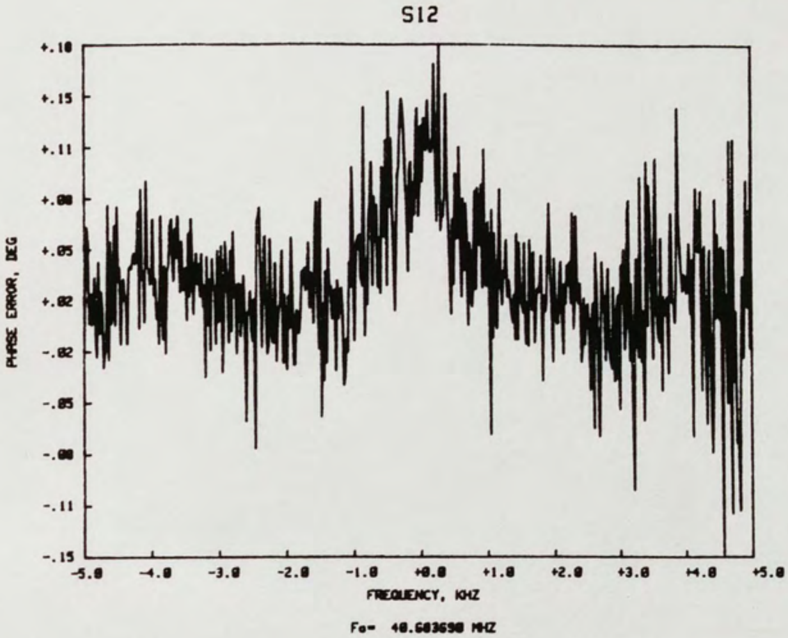

Figure 47. S_{12} Phase Error Plot of Device F83; First Run

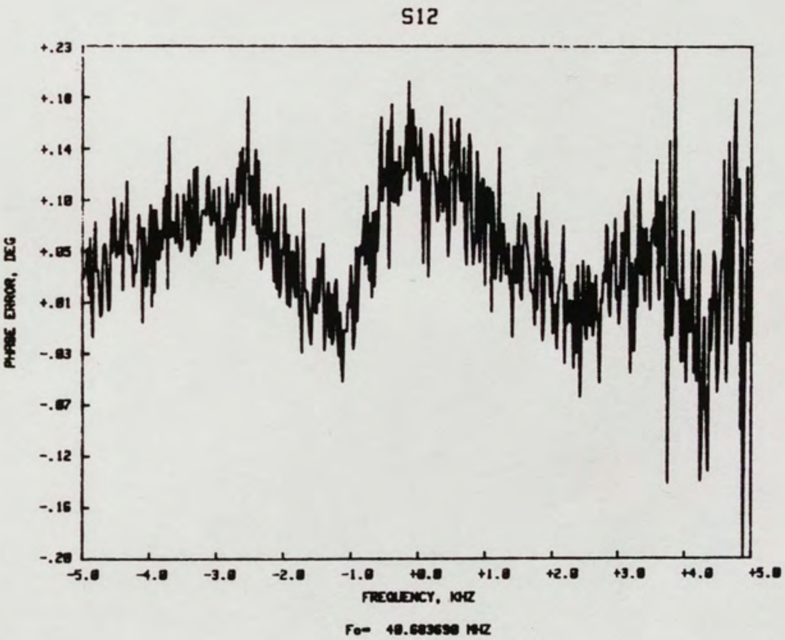

Figure 48. S_{12} Phase Error Plot of Device F83; Second Run

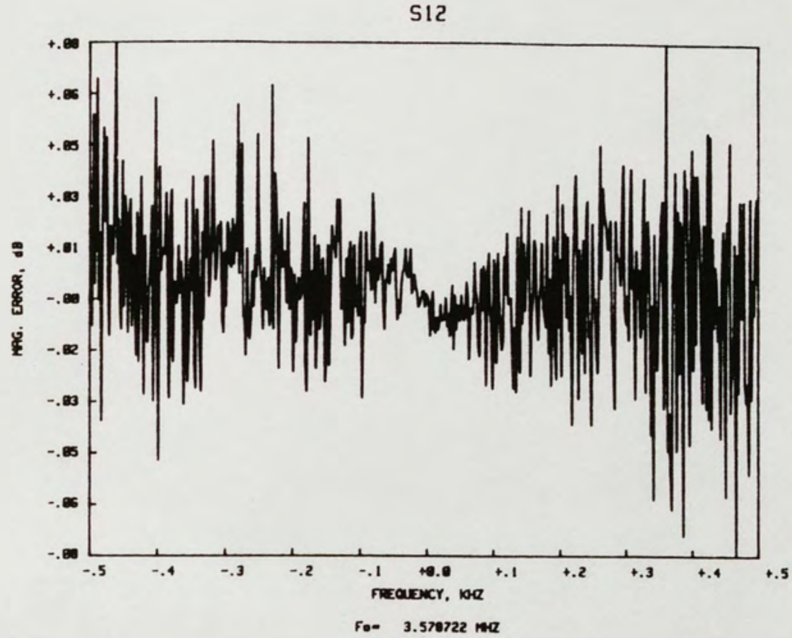

Figure 49. S_{12} Magnitude Error Plot of Device J69; First Run

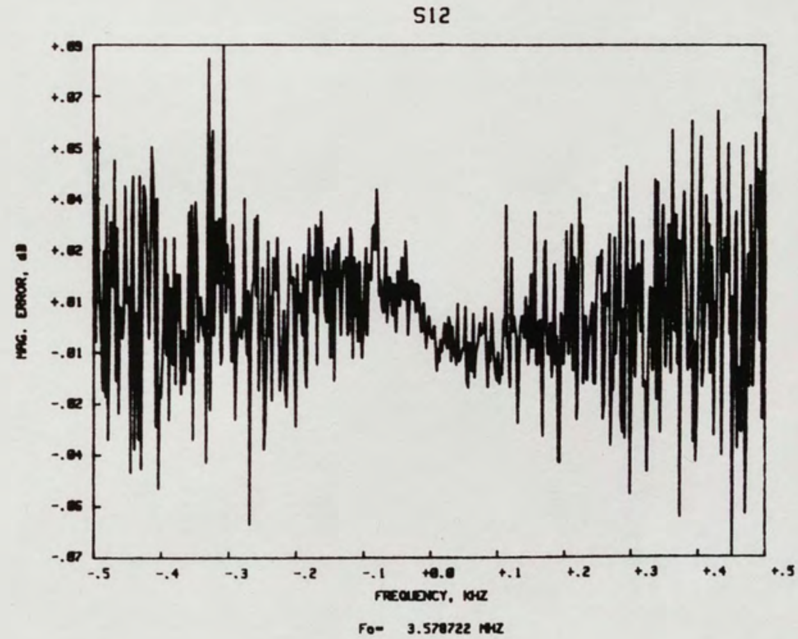

Figure 50. S_{12} Magnitude Error Plot of Device J69; Second Run

The increased errors for both of these runs are noted at lower and higher frequencies where the S_{12} magnitude is lower (see figures 14 and 16). Figures 51 and 52 show the S_{12} phase error plots of device J69 for the first and second run. The error ranges from -0.62 degrees to +0.37 degrees for the first run and from -0.63 degrees to +0.45 degrees for the second run. Increased errors for both runs occur as the S_{12} phase approaches +/- 90 degrees at lower and higher frequencies (see figures 15 and 17).

Figures 53 and 54 show the S_{11} magnitude error plots of device F83 for the first and second run. The first run error ranges from -0.09 dB to +0.05 dB and the second run error ranges from -0.03 dB to +0.05 dB. The increased errors for both runs are noted slightly before and after the resonant frequency where the S_{11} magnitude changes are sharp over a small frequency span (see figures 19 and 21). Figures 55 and 56 show the phase error plots of device F83 for the first and second run. The error ranges from -0.54 degrees to +0.24 degrees on the first run and from -0.37 degrees to +0.28 degrees on the second run. The increased errors for both runs occur slightly before and after the resonant frequency where the S_{11} phase changes are sharp over a small frequency span (see figures 20 and 22). Figures 57 and 58 show the S_{11} magnitude error plots of device J69 for the two runs.

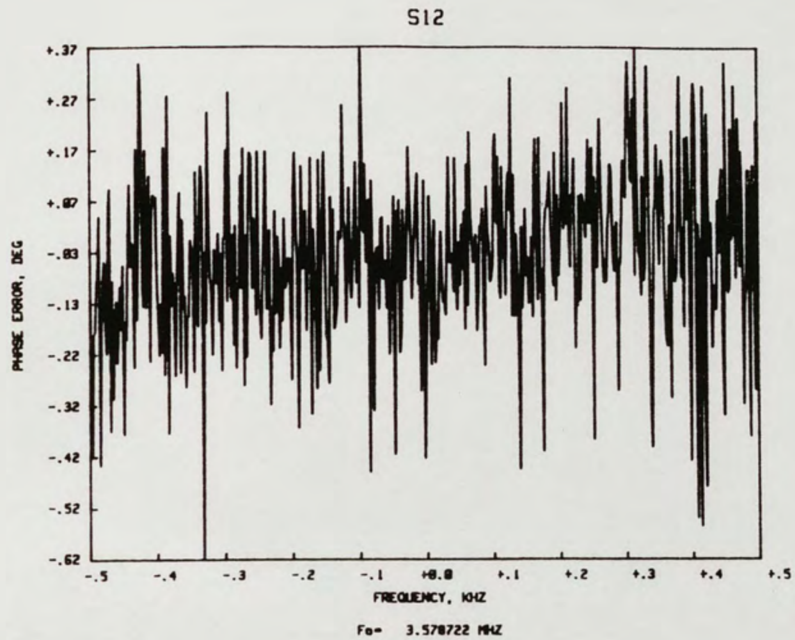

Figure 51. S_{12} Phase Error Plot of Device J69; First Run

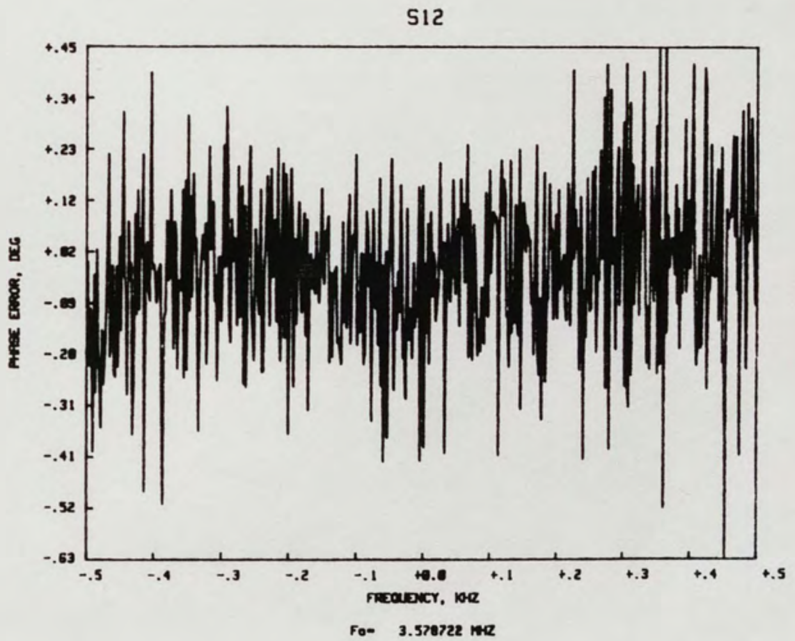

Figure 52. S_{12} Phase Error Plot of Device J69; Second Run

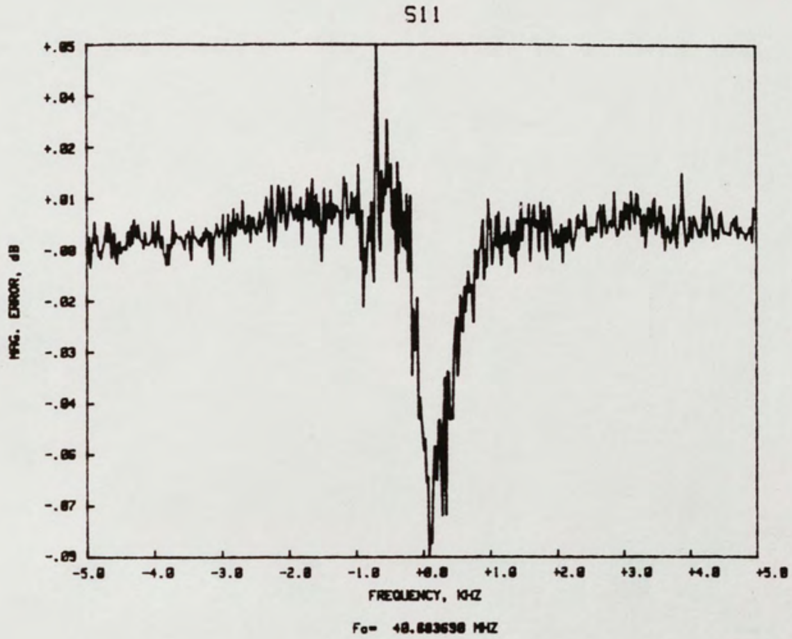

Figure 53. S_{11} Magnitude Error Plot of Device F83; First Run

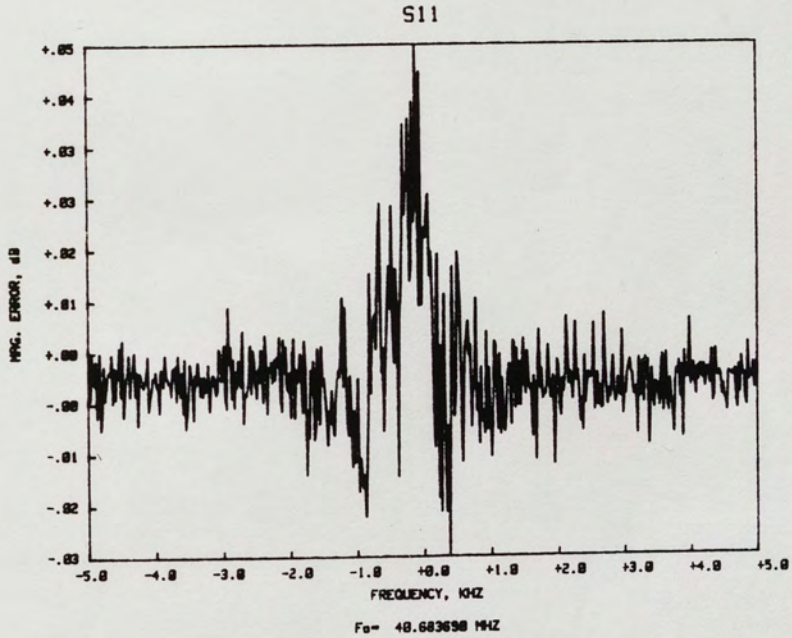

Figure 54. S_{11} Magnitude Error Plot of Device F83; Second Run

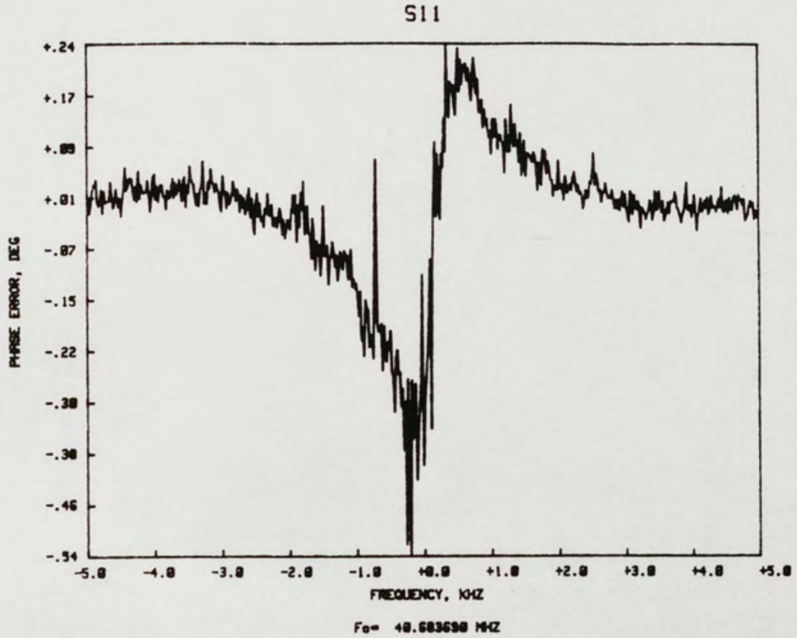

Figure 55. S_{11} Phase Error Plot of Device F83; First Run

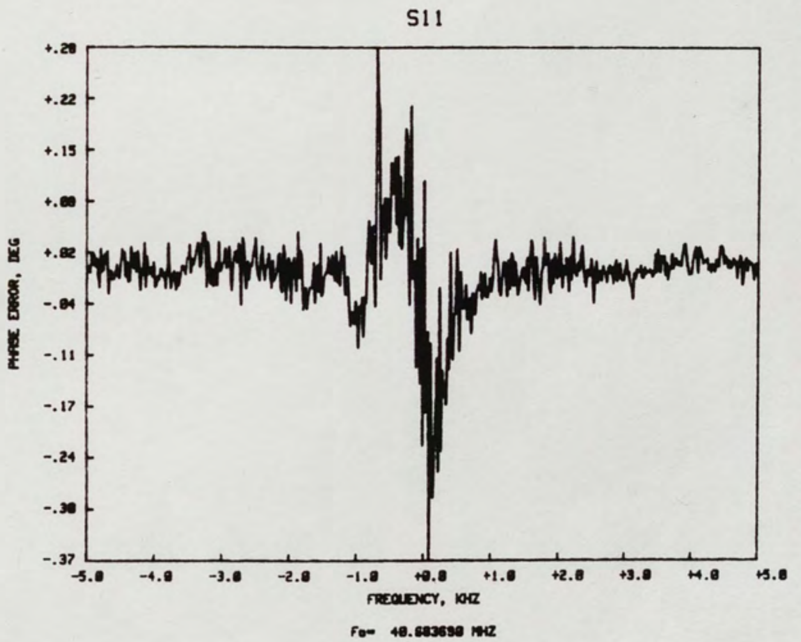

Figure 56. S_{11} Phase Error Plot of Device F83; Second Run

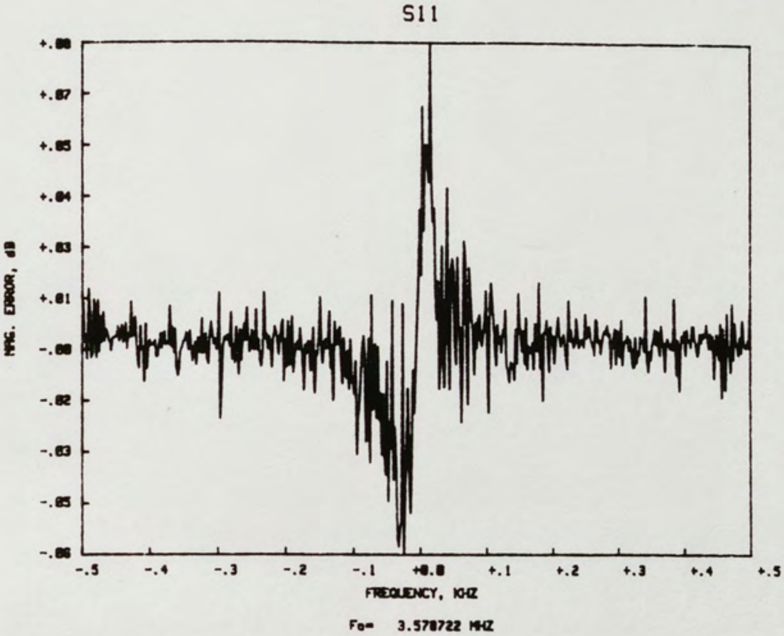

Figure 57. S_{11} Magnitude Error Plot of Device J69; First Run

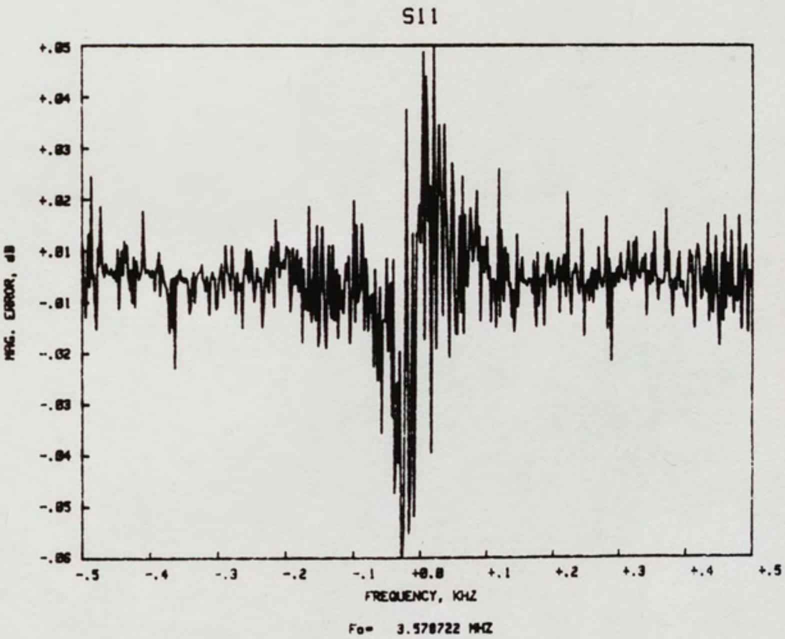

Figure 58. S_{11} Magnitude Error Plot of Device J69; Second Run

The first run error ranges from -0.06 dB to +0.08 dB and the second run error ranges from -0.06 dB to +0.05 dB. As before, error increases are noted where the change in S_{11} magnitude is greatest over a small frequency span slightly before and after resonant frequency (see figures 24 and 26). Figures 59 and 60 show the S_{11} phase error plots of device J69 for the two runs. The first run error ranges from -0.41 degrees to +0.80 degrees with the maximum occurring at the resonant frequency where changes in phase is sharp over a small frequency span (see Figure 25). The second run error ranges from -0.24 degrees to +0.77 degrees with error increases slightly before and after resonant frequency (see Figure 27).

Figures 61 and 62 show the S_{22} magnitude error plots for different values of N, the number of data points. For N=401 the error range in Figure 61 is from -0.06 dB to +0.09 dB. For N=1024 the error range in Figure 62 is from -0.09 dB to +0.06 dB. The error increases for both plots occur slightly before and after resonance where the change in S_{22} magnitude is sharp over a small range of frequencies (see figures 29 and 31). Figures 63 and 64 show the S_{22} phase error plots for N=401 and N=1024, respectively. For N=401 the error range in Figure 63 is from -0.34 degrees to +0.78 degrees with increased error slightly before and after resonant frequency where the change in S_{22} phase is sharp over a small frequency range (see Figure 30).

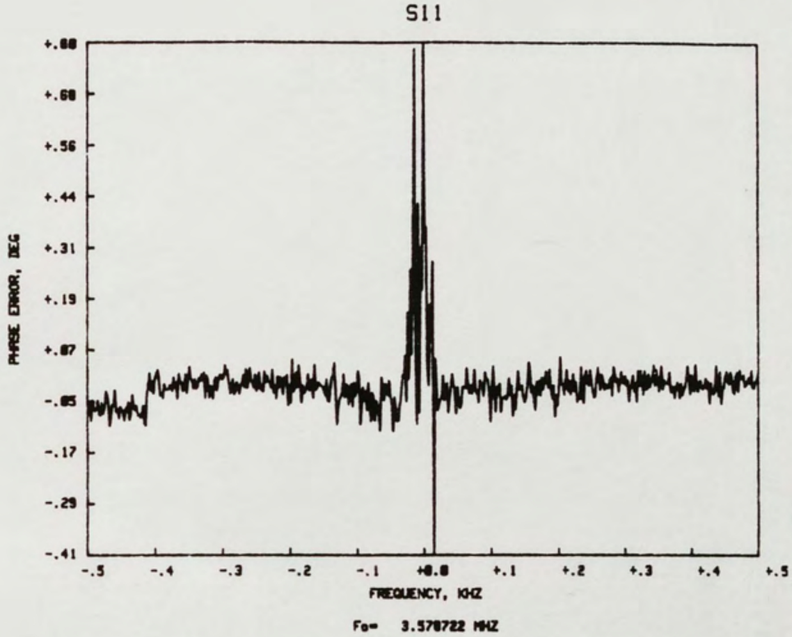

Figure 59. S_{11} Phase Error Plot of Device J69; First Run

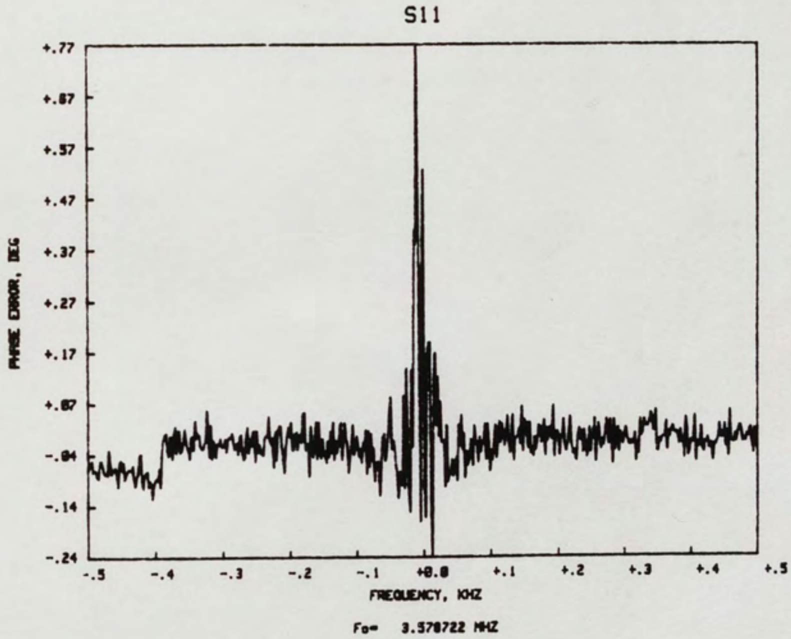

Figure 60. S_{11} Phase Error Plot of Device J69; Second Run

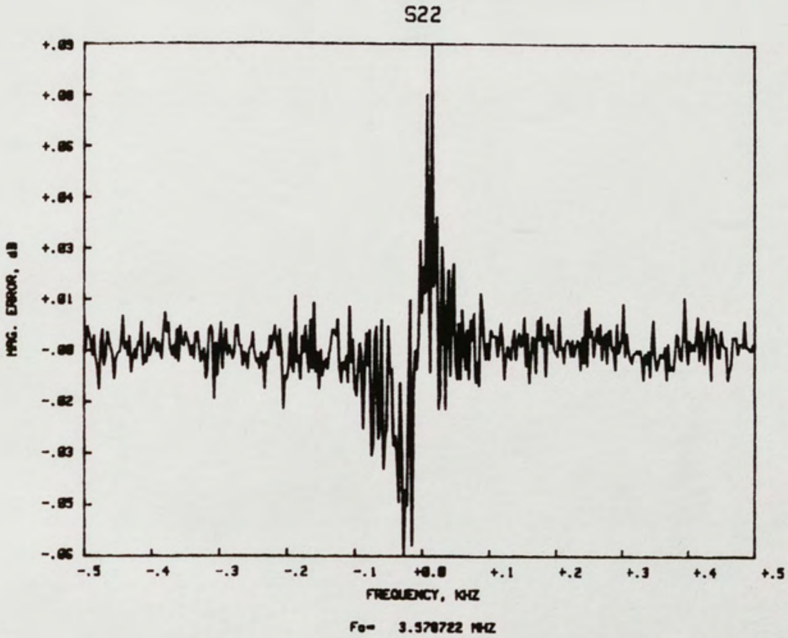

Figure 61. S_{22} Magnitude Error Plot of Device J69 with N=401

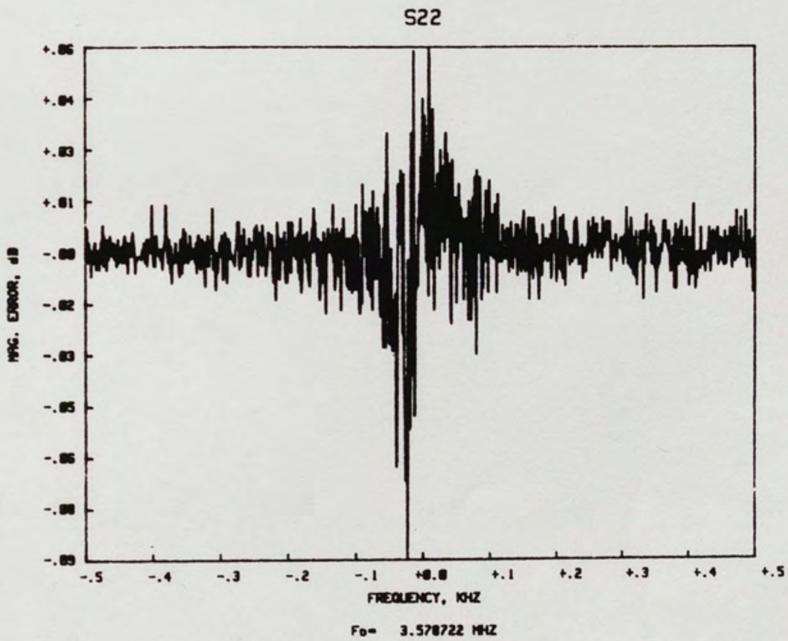

Figure 62. S_{22} Magnitude Error Plot of Device J69 with N=1024

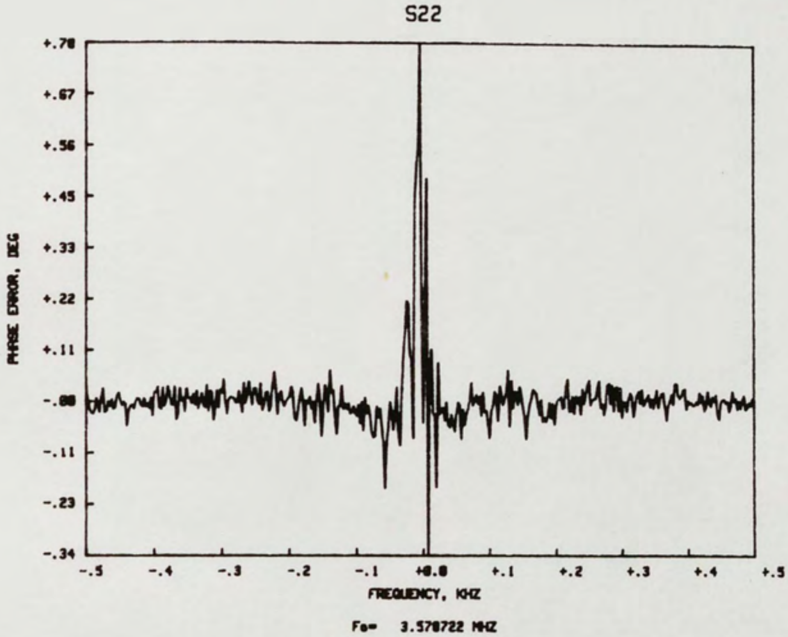

Figure 63. S_{22} Phase Error Plot of Device J69 with N=401

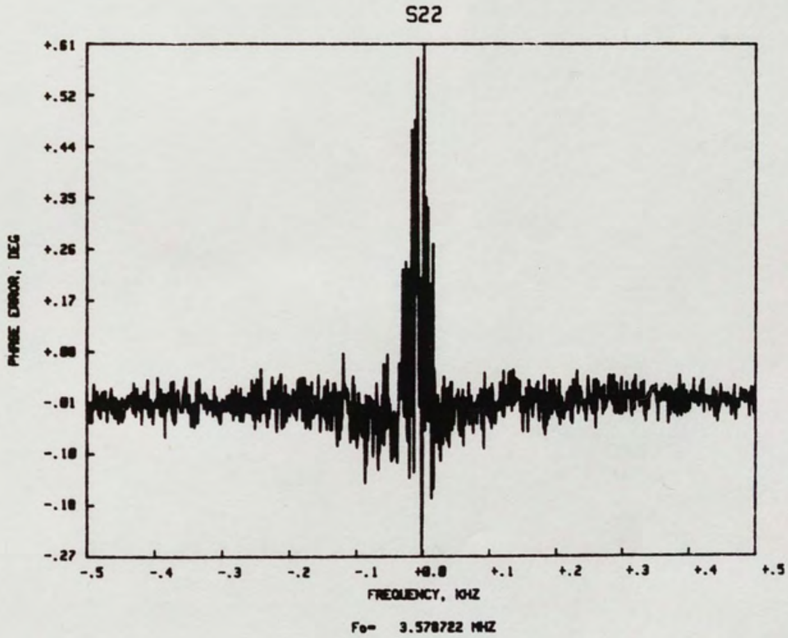

Figure 64. S_{22} Phase Error Plot of Device J69 with N=1024

For N=1024, the error range in Figure 64 is from -0.27 degrees to +0.61 degrees, again with error increases slightly before and after resonant frequency (see Figure 32).

Table 3 shows the maximum errors and their locations as previously discussed for each measurement.

TABLE 3

MAXIMUM ERRORS

Device	Parameter	Method	N	Maximum	Occurrence
1. F83	S_{21} - Magnitude	Dump the Screen	401	+0.04 dB	Higher Freq., Mag. decr.
2. F83	S_{21} - Phase	Dump the Screen	401	+0.19 deg	Sl. Above Res., Hi Phase Slope
3. F83	S_{21} - Magnitude	Define N	401	+0.03 dB	Higher Freq., Mag. decr.
4. F83	S_{21} - Phase	Define N	401	+0.30 deg	Higher Freq., Phase -> -90°
5. F83	S_{21} - Magnitude	Define Df	512	-0.05 dB	Higher Freq., Mag. decr.
6. F83	S_{21} - Phase	Define Df	512	+0.20 deg	Higher Freq., Phase -> -90°
7. F83	S_{12} - Magnitude	Define Df	512	-0.03 dB	Higher Freq., Mag. decr.
8. F83	S_{12} - Phase	Define Df	512	+0.18 deg	Sl. Above Res., Hi Phase Slope
9. F83	S_{12} - Magnitude	Define Df	512	+0.03 dB	Higher Freq., Mag. decr.
10. F83	S_{12} - Phase	Define Df	512	+0.23 deg	Higher Freq., Phase -> -90°
11. J69	S_{12} - Magnitude	Define Df	512	+/-0.08 dB	Lo&Hi Freq., Mag. decr.
12. J69	S_{12} - Phase	Define Df	512	-0.62 deg	Lower Freq., Phase -> 90°
13. J69	S_{12} - Magnitude	Define Df	512	+0.09 dB	Higher Freq., Mag. decr.
14. J69	S_{12} - Phase	Define Df	512	-0.63 deg	Higher Freq., Phase -> -90°
15. F83	S_{11} - Magnitude	Define Df	512	-0.09 dB	Sl. Below Res., Hi Mag. Slope
16. F83	S_{11} - Phase	Define Df	512	-0.54 deg	Sl. Below Res., Hi Phase Slope
17. F83	S_{11} - Magnitude	Define Df	512	+0.05 dB	Sl. Below Res., Hi Mag. Slope
18. F83	S_{11} - Phase	Define Df	512	-0.37 deg	Sl. Above Res., Hi Phase Slope
19. J69	S_{11} - Magnitude	Define Df	512	+0.08 dB	Sl. Above Res., Hi Mag. Slope
20. J69	S_{11} - Phase	Define Df	512	+0.80 deg	Res. Freq., Hi Phase Slope
21. J69	S_{11} - Magnitude	Define Df	512	-0.06 dB	Sl. Below Res., Hi Mag. Slope
22. J69	S_{11} - Phase	Define Df	512	+0.77 deg	Sl. Below Res., Hi Phase Slope
23. J69	S_{22} - Magnitude	Define N	401	+0.09 dB	Sl. Above Res., Hi Mag. Slope
24. J69	S_{22} - Phase	Define N	401	+0.78 deg	Sl. Below Res., Hi Phase Slope
25. J69	S_{22} - Magnitude	Define N	1024	-0.09 dB	Sl. Below Res., Hi Mag. Slope
26. J69	S_{22} - Phase	Define N	1024	+0.61 deg	Sl. Above Res., Hi Phase Slope

DISCUSSION AND CONCLUSION

Resonators

A resonator is a device which allows the greatest flow of current at a certain frequency. In a quartz crystal resonator, a thin flat piece of quartz is placed between two electrodes. If an alternating electric signal is applied to these electrodes, the piezoelectric properties of quartz will cause the quartz to vibrate. When the frequency of this electric signal is very near the mechanical resonance of the quartz slab, the amplitude of the vibrations become very large. The strain of these vibrations causes the quartz to produce a sinusoidal electric field which controls the effective impedance between the two electrodes. This impedance then possesses a very high Q [1].

The Q, or quality factor, is defined by the equation

$$Q = \frac{f_o}{B} \quad ,$$

where f_o is the frequency of resonance and B is the bandwidth where the magnitude is $1/\sqrt{2}$ times the resonant magnitude [7]. From Figure 9, the Q of device F83 is approximately 16,000 and from Figure 14, the Q of device J69 is approximately 36,000.

Error Sources

When considering errors there are several possible sources. Systematic, random, drift, and operator errors can all cause deviations in magnitude and phase measurement results between sweeps [8]. These are discussed in the section to follow herein.

Discussion of Results

As can be seen from Table 2, when comparing methods of data acquisition in items 1-8, the magnitude at resonance showed the same percent difference. When the magnitude ranges were compared, the "Define the Delta Frequency" method had a somewhat smaller percent difference when compared to the "Dump the Screen" method than did the "Define the Number of Data Points" method. The phase at resonance and phase range also had smaller percent differences when comparing the "Define the Delta Frequency" method to the "Dump the Screen" method. All error sources can combine to cause differences between measurements, however the most probable cause of discrepancy between methods of data acquisition is systematic error. The degree to which residual systematic errors remaining after calibration/normalization combine is affected by the measurement method [8].

From items 9-16 of Table 2 one can compare consecutive runs measuring S_{12}. The magnitude at resonance had the same percent difference for consecutive runs on the two devices while the magnitude and phase ranges had a smaller percent difference for device J69. The phase at resonance had a smaller percent difference between runs for device F83. From items 17-24 of Table 2 one can compare consecutive runs measuring S_{11}. The magnitude at resonance, magnitude range and phase range had smaller percent differences between consecutive runs for device J69 while the phase at resonance had a smaller percent difference between runs for device F83. Errors due to temperature drift can cause differences between measurement sweeps. Frequency drift is caused by the device under test while instrumentation drift is caused by the thermal expansion characteristics of the interconnecting cables within the test set [8].

From items 25-28 of Table 2, one can compare the results of runs made with a varying number of data points. The percent differences between runs made defining N to be 401 and then 1024 were approximately a fourth of one percent with exception of the phase at resonance which did not differ at all. Accuracy and smoothness of the trace are dependent upon sweep resolution.

One would expect discrepancies between measurements utilizing sweep resolutions of different sizes, especially one being over two and a half times larger than the other.

In Table 3 the maximum errors are summarized. From items 1-6 one can compare the S_{21} errors of different data acquisition methods. The "Define the Number of Data Points" method had the smallest magnitude error while the "Dump the Screen" method had the smallest phase error. Most of the S_{21} errors occurred when the magnitude was small and as the phase approached -90^{o}. None of the errors, however, are outside the network analyzer specifications (see Appendix A) of +/- 0.15 decibels and +/- 2.0 degrees. From items 7-14 of Table 3 one can compare the errors of the two devices when measuring S_{12}. The magnitude and phase errors were smaller for device F83. Again, most of the S_{12} errors occurred when the magnitude was small and as the phase approached -90^{o}. While errors are within specifications, all errors can combine and it is sometimes difficult to single out one specific source. Residual systematic errors remaining after calibration/normalization result from the imperfections in the calibration standards, the connector interface, the interconnecting cables and the instrumentation [8]. It may be noted that the default resolution bandwidth is the maximum at 1 kHz and thus the pre-sweep settling time is minimum at 22 ms. Reduction in bandwidth would lower the noise floor and result in an increase in settling time. This however would necessitate a longer sweep or sample time for more accurate results [4].

When measuring S_{11} (items 15-22) the magnitude errors were comparably the same for both devices while the phase errors were smaller for device F83. All of the S_{11} errors occurred at or near resonance where the change in magnitude and phase was great over a small frequency range. Again, all errors were within specifications. It appears that a frequency drift has taken place. If a drift to the left occurred in device F83 between measurement sweeps the magnitude errors would be positive during pre-resonance and negative during post-resonance. The phase errors would be positive before resonance, become negative immediately before and after resonance and then become positive again. This can be observed in figures 53 to 56. If a frequency drift to the right occurred in device J69 the magnitude errors would be negative during pre-resonance and positive during post-resonance. The phase errors would be positive during pre-resonance and negative during post-resonance. This can be observed in figures 57 to 60.

From items 23 to 26 of Table 3, one can compare the errors when runs are made with different values for N, the number of data points. The magnitude errors were the same for N equaling 401 and 1024. The phase error was somewhat smaller for N=1024. All of the S_{22} errors occurred near resonance where the change in magnitude and phase was great over a small range of frequency. All errors were within specifications, however as with the S_{11} measurements, the second measurement sweep of device J69 appears to have drifted to the right.

Observe from Table 3 that the maximum magnitude error ranged from -0.09 dB to +0.09 dB and the maximum phase error ranged from -0.63 degrees to + 0.78 degrees. These results are more than 50% better than the specifications given for the network analyzer, however these errors still bound the accuracy of measurement results and must be taken into consideration.

As noted from figures 34 to 38, measurements of the SAW device were taken in the frequency domain and successfully transformed via a separate computer program into the time domain thus giving greater dynamic range and accuracy.

Problems encountered during the development of the computer program stemmed mainly from its size. The author would have liked to calibrate all of the scattering parameters rather than calibrating one and normalizing the remaining three. The author would also have liked to make corrections for the errors incurred in the measurements.

In summary, a program was written which offers the advantages of a choice of data acquisition method, option of a greater number of sample frequencies, permanent record of results, error analysis, and storage of data for future manipulation. With these advantages the program overcomes many of the limitations encountered using only the analyzer instrumentation for device testing.

APPENDICES

APPENDIX A

SPECIFICATIONS FOR THE HP 3577A AND THE HP 35677A

See reference 4

HP 3577A

Magnitude Characteristics

Range: Maximum Input Level to Sensitivity.

Resolution: 0.001 dB (log); 5 digits (linear).

Accuracy (at 100 kHz, 25^{o}C, and Maximum Input Level): +/- 0.15 dB (50 Ohms)

Accuracy and frequency response errors, and effects of different input attenuation can be calibrated out with normalization.

Dynamic Accuracy:

Input Level Relative to Maximum Allowable	Error
0 dB to -10 dB	+/- 0.04 dB
-10 dB to -50 dB	+/- 0.02 dB
-50 dB to -60 dB	+/- 0.05 dB
-60 dB to -80 dB	+/- 0.15 dB
-80 dB to -90 dB	+/- 0.75 dB
-90 dB to -100 dB	+/- 0.75 dB

Frequency Response: Specifications apply when inputs are driven from a 50 Ohm source impedance

Frequency	Error
20 Hz to 20 MHz	0.3 dBpp
5 Hz to 200 MHz	0.4 dBpp
5 Hz to 200 MHz	-----

Phase Characteristics

Range: +/- 180 degrees.

Resolution: 0.005 deg (0.0001 rad).

Accuracy (at 100 kHz, 25^{o}C, and Maximum Input Level): +/- 2.0 deg.

Accuracy and frequency response errors, and effects of different input attenuation can be calibrated out with normalization.

Dynamic Accuracy:

Input Level Relative to Maximum Allowable	Error
0 dB to -10 dB	+/- 0.4 deg
-10 dB to -50 dB	+/- 0.2 deg
-50 dB to -60 dB	+/- 0.5 deg
-60 dB to -80 dB	+/- 1.5 deg
-80 dB to -90 dB	+/- 7.5 deg
-90 dB to -100 dB	+/- .75 deg

Frequency Response: Specifications apply when inputs are driven from a 50 Ohm source impedance

Frequency	Error
20 Hz to 20 MHz	2 deg pp
5 Hz to 200 MHz	10 deg pp
5 Hz to 200 MHz	-----

<u>HP 35677A</u>

Frequency Range: 100 kHz to 200 MHz

Test Port Impedance: 50 Ohms

Frequency Response:

Transmission (S_{21}, S_{12}): +/- 1 dB, +/- 5 deg.

Reflection (S_{11}, S_{22}): +/- 1 dB, +/- 5 deg.

APPENDIX B

DERIVATION OF S_{11} CALIBRATION EQUATION

See references 3 and 9

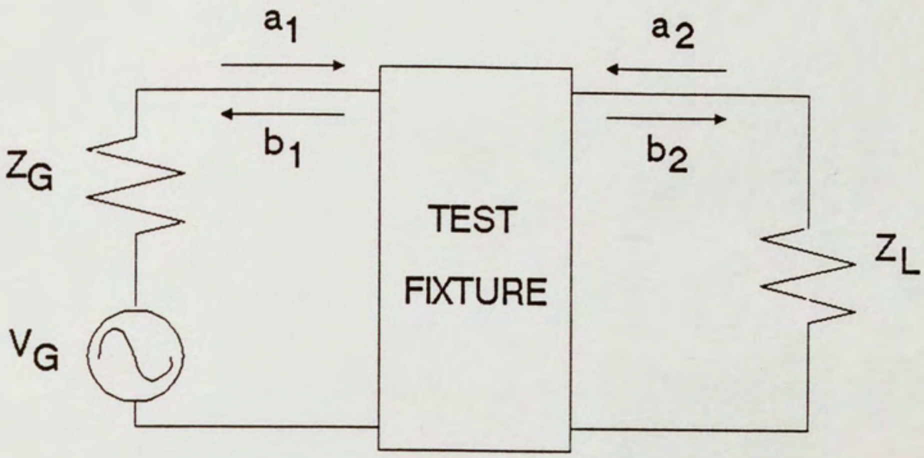

Figure 65. Diagram of a Two Port Network

The scattering parameters of the one-port network of Figure 65 are defined by the following equations:

$$b_1 = S_{11}a_1 + S_{12}a_2 \tag{1}$$

$$b_2 = S_{21}a_1 + S_{22}a_2 \tag{2}$$

To find the equation for the corrected value of the input reflection, S_{11}, first solve equation (2) for a_2/a_1.

$$\frac{b_2}{a_2} = S_{21}\frac{a_1}{a_2} + S_{22}$$

$$\frac{\frac{b_2}{a_2} - S_{22}}{S_{21}} = \frac{a_1}{a_2}$$

or

$$\frac{a_2}{a_1}=\frac{S_{21}}{\frac{b_2}{a_2}-S_{22}} \tag{3}$$

Now solve equation (1) for b_1/a_1 then substitute the value of a_2/a_1 from equation (3)

$$\frac{b_1}{a_1}=S_{11}+S_{12}\frac{a_2}{a_1} \tag{4}$$

$$\frac{b_1}{a_1}=S_{11}+\frac{S_{12}S_{21}}{\frac{b_2}{a_2}-S_{22}} \tag{5}$$

For calibration, let Z_L of Figure 65 be equal to a known impedance. Then, since all the power is absorbed and there is no reflection, a_2 will equal zero and so equation (4) becomes

$$\frac{b_1}{a_1}=S_{11}$$

For this case, let

$$\frac{b_1}{a_1}=\Gamma_t=e_{00}$$

where Γ_t is measured with the load in place. Next, let $Z_L=0$ as when replaced by a short. Then $a_2/b_2=-1$ due to a 180 degree phase shift. Substituting, equation (5) becomes

$$\frac{b_1}{a_1}=S_{11}+\frac{S_{12}S_{21}}{-1-S_{22}}$$

or

$$\frac{b_1}{a_1} = S_{11} - \frac{S_{12}S_{21}}{1 + S_{22}} \tag{6}$$

Let two additional error terms be defined as $e_{01}=S_{12}S_{21}$ and $e_{11}=S_{22}$. Then let $\Gamma_s=b_1/a_1$ for the measured value when the short is in place. Equation (6) then becomes

$$\Gamma_s = e_{00} - \frac{e_{01}}{1 + e_{11}} \tag{7}$$

Finally, replace the short with an open. Then, with no phase shift, $a_2/b_2=1$ and substituting, equation (5) becomes

$$\frac{b_1}{a_1} = S_{11} + \frac{S_{12}S_{21}}{1 - S_{22}} \tag{8}$$

Using the error terms and defining $\Gamma_o=b_1/a_1$ as the measured value when the open is in place, equation (8) becomes

$$\Gamma_o = e_{00} + \frac{e_{01}}{1 - e_{11}} \tag{9}$$

The error terms can be found from equations (7) and (9). Remembering that $\Gamma_t = e_{00}$, from equation (7)

$$\Gamma_t - \Gamma_s = \frac{e_{01}}{1 + e_{11}}$$

$$e_{01} = \left(\Gamma_t - \Gamma_s\right)\left(1 + e_{11}\right) \tag{10}$$

Substitute this value for e_{01} into equation (9)

$$\Gamma_o - \Gamma_t = \frac{(\Gamma_t - \Gamma_s)(1 + e_{11})}{(1 - e_{11})}$$

$$(\Gamma_o - \Gamma_t)(1 - e_{11}) = (\Gamma_t - \Gamma_s)(1 + e_{11})$$

$$\Gamma_o - \Gamma_t - e_{11}\Gamma_o + e_{11}\Gamma_t = \Gamma_t - \Gamma_s + e_{11}\Gamma_t - e_{11}\Gamma_s$$

$$e_{11}(\Gamma_s - \Gamma_o) = 2\Gamma_t - \Gamma_s - \Gamma_o$$

$$e_{11} = \frac{2\Gamma_t - \Gamma_s - \Gamma_o}{\Gamma_s - \Gamma_o} \tag{11}$$

Replace e_{11} in equation (10) with equation (11)

$$e_{01} = (\Gamma_t - \Gamma_s)\left(1 + \frac{2\Gamma_t - \Gamma_s - \Gamma_o}{\Gamma_s - \Gamma_o}\right)$$

$$e_{01} = (\Gamma_t - \Gamma_s)\left(\frac{\Gamma_s - \Gamma_o + 2\Gamma_t - \Gamma_s - \Gamma_o}{\Gamma_s - \Gamma_o}\right)$$

$$e_{01} = \frac{(\Gamma_t - \Gamma_s)(2\Gamma_t - 2\Gamma_o)}{\Gamma_s - \Gamma_o} \tag{12}$$

With the test device in place $a_2/b_2=S_{11}$ and equation (5) becomes

$$\frac{b_1}{a_1} = e_{00} + \frac{e_{01}}{\frac{1}{S_{11}} - e_{11}}$$

$$\frac{b_1}{a_1} = e_{00} + \frac{S_{11}e_{01}}{1 - S_{11}e_{11}} \tag{13}$$

Here let $b_1/a_1=M_{meas}$ then solve equation (13) for S_{11}

$$M_{meas}\left(1 - S_{11}e_{11}\right) = e_{oo}\left(1 - S_{11}e_{11}\right) + S_{11}e_{01}$$

$$M_{meas}S_{11}e_{11} - S_{11}e_{11}e_{oo} + S_{11}e_{01} = M_{meas} - e_{oo}$$

$$S_{11} = \frac{M_{meas} - e_{oo}}{M_{meas}e_{11} - e_{11}e_{oo} + e_{01}} \tag{14}$$

Substitute the values for the error terms

$$S_{11} = \frac{M_{meas} - \Gamma_t}{M_{meas}\left(\frac{2\Gamma_t - \Gamma_s - \Gamma_o}{\Gamma_s - \Gamma_o}\right) - \left(\frac{2\Gamma_t - \Gamma_s - \Gamma_o}{\Gamma_s - \Gamma_o}\right)\Gamma_t + \frac{(\Gamma_t - \Gamma_s)(2\Gamma_t - 2\Gamma_o)}{\Gamma_s - \Gamma_o}}$$

$$S_{11} = \frac{M_{meas} - \Gamma_t}{M_{meas}\left(\frac{2\Gamma_t - \Gamma_s - \Gamma_o}{\Gamma_s - \Gamma_o}\right) + \left(\frac{-2\Gamma_t^2 + \Gamma_s\Gamma_t + \Gamma_o\Gamma_t + 2\Gamma_t^2 - 2\Gamma_o\Gamma_t - 2\Gamma_s\Gamma_t + 2\Gamma_s\Gamma_o}{\Gamma_s - \Gamma_o}\right)}$$

$$S_{11} = \frac{M_{meas} - \Gamma_t}{M_{meas}\left(\frac{2\Gamma_t - \Gamma_s - \Gamma_o}{\Gamma_s - \Gamma_o}\right) + \left(\frac{2\Gamma_s\Gamma_o - \Gamma_t(\Gamma_s + \Gamma_o)}{\Gamma_s - \Gamma_o}\right)} \tag{15}$$

Letting the factor for source match be

$$S_f = \frac{2\Gamma_t - \Gamma_s - \Gamma_o}{\Gamma_s - \Gamma_o}$$

the correction factor for directivity be

$$D = \Gamma_t$$

and the correction factor for transmission be

$$T_f = \frac{2\Gamma_s \Gamma_o - \Gamma_t(\Gamma_s + \Gamma_o)}{\Gamma_s - \Gamma_o}$$

Then equation (15) can be written more simply as

$$S_{11} = \frac{M_{meas} - D}{M_{meas} S_f + T_f} \tag{16}$$

APPENDIX C

COMPUTER LISTING FOR "SCAT"

```
10      ! UNIVERSITY OF CENTRAL FLORIDA
20      ! DEPARTMENT OF ELECTRICAL ENGINEERING AND COMMUNICATION SCIENCES
30      ! SPRING, SUMMER, AND FALL TERMS, 1987
40      ! SALLIE LAYTON DOUGLAS
50      !
60      ! REMOTE DATA ACQUISITION AND SYSTEMATIC ERROR ANALYSIS
70      !
80      ! MEASUREMENT SETUP
90      OPTION BASE 1                                   !SETS LOWER BOUND FOR DIMENSIONING
100                                                     ! ARRAYS AT 1 RATHER THAN 0
110     INPUT "Hardkey=SPCL FCTN, Softkey=TALKONLY OFF. Press CONT.",Y
120     ! THE HP 3577A MUST BE ABLE TO TALK AND LISTEN TO BE OPERATED REMOTELY.
130     REMOTE 711                                      !SWITCHES CONTROL OF THE HP 3577A
140                                                     ! FROM LOCAL TO REMOTE
150     DIM A(1024),B(1024),C(1024),D(1024),E(1024),Dn(1024),En(1024),F(1024)
160     DIM G(1024),H(1024),M(1024),N(1024),O(1024),P(1024),Q(1024),R(1024)
170     OUTPUT 711;"IPR;"                               !INSTRUMENT PRESET
180     INPUT "Start frequency = ? Enter in MHz then press CONT.",Afreq
190     OUTPUT 711;"FRA;",Afreq,"MHZ;"                  !START FREQUENCY
200     Y=(Afreq=0)                                     !CHECK START FREQUENCY
210     IF Y THEN GOTO 250                              !IF ZERO, THEN GO TO FILL THE
220                                                     ! FIRST VALUES OF THE ARRAYS USED
230                                                     ! WITH S21 FOR FFT ON SAW DEVICE
240     GOTO 310                                        !ELSE, CONTINUE
250     Dn(1)=0
260     En(1)=0
270     B(1)=-100
280     C(1)=0
290     Ii=2                                            !SET ARRAY START VARIABLE AT 2
300     GOTO 320                                        !CONTINUE
310     Ii=1                                            !SET ARRAY START VARIABLE AT 1
320     INPUT "Stop frequency = ? Enter in MHz then press CONT.",Bfreq
330     OUTPUT 711;"FRB;",Bfreq,"MHZ;"                  !STOP FREQUENCY
331     INPUT "Source output signal level = ? Enter in dBm then press CONT.",Amp
340     OUTPUT 711;"AMP;",Amp,"DBM;"                    !AMPLITUDE
350     OUTPUT 711;"DSF;",TR2;DF5;"                     !DISPLAY TRACE 2, DEFINE AS PHASE
360     OUTPUT 711;"TR1;"                               !TURN TRACE 1 BACK ON (DEFAULT
370                                                     ! FUNCTION FOR TR 1 IS LOG. MAG.)
380     GOSUB 7120                                      !GOTO DATA ACQUISITION METHOD SUBR.
390     REDIM A(N),B(N),C(N),D(N),E(N),Dn(N),En(N),F(N)
400     REDIM G(N),H(N),M(N),N(N),O(N),P(N),Q(N),R(N)
410     E=0                                             !PRESET ERROR RUN FLAG
420     INPUT "Do you want dual sweeps for system error checks?",X$
430     IF X$="N" THEN GOTO 460
440     IF X$="N" THEN GOTO 450
450     E=1                                             !SET ERROR RUN FLAG
460     ! MEASUREMENT SETUP COMPLETE
470     INPUT "Setup complete. Press CONT.",Y
480     INPUT "Do you want to measure S21?",X$
490     IF X$="N" THEN GOTO 570
500     IF X$="Y" THEN GOTO 510
510     ! MEASUREMENT OF S21; FORWARD GAIN AND PHASE
520     S=1                                             !SET S PARAMETER FLAG TO 1
530     GOSUB 8040                                      !GO TO CALIBRATION SUBROUTINE
540                                                     ! TO NORMALIZE WITH THE "THRU"
550     GOSUB 950                                       !GOING TO TAKE DATA FROM THE DUT
560     INPUT "Measurement of S21 complete. Press CONT for S12.",Y
570     INPUT "Do you want to measure S12 ?",X$
580     IF X$="N" THEN GOTO 670
590     IF X$="Y" THEN GOTO 600
600     ! MEASUREMENT OF S12; REVERSE LOSS AND REVERSE PHASE ANGLE
610     S=2                                             !SET S PARAMETER FLAG TO 2
620     OUTPUT 711;"I12;TR2;I12;TR1;"                   !INPUT = S12 FOR BOTH TRACES
630     GOSUB 8040                                      !GO TO CALIBRATION SUBROUTINE
640                                                     ! TO NORMALIZE WITH THE "THRU"
650     GOSUB 950                                       !GO TO TAKE DATA FROM THE DUT
660     INPUT "Measurement of S12 complete. Press CONT for S11.",Y
670     INPUT "Do you want to measure S11 ?",X$
680     IF X$="N" THEN GOTO 810
690     IF X$="Y" THEN GOTO 700
700     ! MEASUREMENT OF S11; INPUT RETURN LOSS AND CORRESPONDING PHASE
710     S=3                                             !SET S PARAMETER FLAG TO 3
```

```
720   OUTPUT 711;"I11;TR2;I11;TR1;"                     !INPUT = S11 FOR BOTH TRACES
730   OUTPUT 711;"DF6;"                                 !CHANGE TRACE 1 TO LINEAR MAGNITUDE
740   GOSUB 9020                                        !GO TO ONE PORT FULL
750                                                     ! CALIBRATION SUBROUTINE
760                                                     ! TO CALIBRATE WITH THE "OPEN",
770                                                     ! "SHORT", AND "LOAD"
780   GOSUB 950                                         !GO TO TAKE DATA FROM THE DUT
790   OUTPUT 711;"DF7;"                                 !RETURN TRACE 1 TO LOG MAGNITUDE
800   INPUT "Measurement of S11 complete. Press CONT for S22.",Y
810   INPUT "Do you want to measure S22 ?",X$
820   IF X$="N" THEN GOTO 920
830   IF X$="Y" THEN GOTO 840
840   ! MEASUREMENT OF S22; OUTPUT REFLECTION COEFFICIENT
850   S=4                                               !SET S PARAMETER FLAG TO 4
860   OUTPUT 711;"TR1;I22;TR2;I22;TR1;"                 !INPUT = S22 FOR BOTH TRACES
870   GOSUB 8040                                        !GO TO CALIBRATION SUBROUTINE
880                                                     ! TO NORMALIZE WITH THE "OPEN"
890   GOSUB 950                                         !GO TO TAKE DATA FROM THE DUT
900   INPUT "Measurement of S22 complete. Press CONT to end.",Y
910   GOTO 930
920   INPUT "Press CONT to end.",Y
930   END
940   !
950   ! TAKE DATA FROM THE DEVICE UNDER TEST
960   OUTPUT 711;"ST1;"                                 !LINEAR FREQUENCY SWEEP
970   Y=(Du=1)                                          !CHECK THE "DUMP THE SCREEN" FLAG
980   IF Y THEN GOTO 1040
990   Y=(Fr=1)                                          !CHECK THE "DEFINE dF" FLAG
1000  IF Y THEN GOTO 3830
1010  Y=(Nu=1)                                          !CHECK THE "DEFINE N" FLAG
1020  IF Y THEN GOTO 2350
1030  !
1040  ! THIS SECTION DUMPS ALL OF THE 401 DATA POINTS FROM THE HP 3577A SCREEN
1050  Re=0                                              !PRESET ERROR RUN "ONCE THROUGH"
1060  Rp=0                                              !PRESET ERROR RUN "PRINT/PLOT"
1070  DISP "Please wait. Measurements are being taken."
1080  OUTPUT 711;"SM2;TKM;FM1;DT1;"                     !SINGLE SWEEP, TAKE MEASUREMENT,
1090                                                    ! PUT IN ASCII FORM, AND
1100                                                    ! DUMP TRACE 1 (MAGNITUDE)
1110  ENTER 711 USING "#,F";B(*)                        !ENTER DATA INTO ARRAY B
1120  OUTPUT 711;"SM2;TKM;FM1;DT2;"                     !SINGLE SWEEP, TAKE MEASUREMENT,
1130                                                    ! PUT IN ASCII FORM, AND
1140                                                    ! DUMP TRACE 2 (PHASE)
1150  ENTER 711 USING "#,F";C(*)                        !ENTER DATA INTO ARRAY C
1160  MAT D=B                                           !IN PREPARATION FOR MATH, LOAD
1170  MAT E=C                                           !ARRAYS B AND C INTO ARRAY D AND E
1180  Y=(S=3)                                           !CHECK THE S11 FLAG
1190  IF Y THEN GOTO 1230                               !IF SET, SKIP THE FOLLOWING MATH
1200  MAT Q=D-Dn                                        !SUBTRACT (dB) NORMALIZING ARRAY
1210  MAT R=E-En                                        !SUBTRACT (PHASE) NORMALIZING ARRAY
1220  GOTO 1260
1230  GOSUB 11900                                       !GO TO END OF THE ONE PORT FULL
1240                                                    ! CALIBRATION SUBROUTINE TO FIND
1250                                                    ! THE CORRECTED MEASUREMENT
1260  MAT E=R                                           !LOAD CALIBRATED PHASE ARRAY, R,
1270                                                    ! INTO ARRAY E
1280  GOSUB 12480                                       !GO TO CHECK FOR 360 DEGREE SHIFT
1290  MAT R=E                                           !RELOAD CALIBRATED PHASE ARRAY, R,
1300                                                    ! WITH CORRECTED PHASE ARRAY, E
1310  Y=(E=1)                                           !CHECK ERROR RUN FLAG
1320  IF Y THEN GOTO 1340                               !IF SET, CONTINUE
1330  GOTO 1430                                         !ELSE, GO TO PRINT ARRAYS B AND C
1340  Y=(Re=0)                                          !CHECK ERROR RUN "ONCE
1350                                                    ! THROUGH" FLAG
1360  IF Y THEN GOTO 1390                               !IF NOT SET, GO TO STORE
1370                                                    ! FIRST SWEEP
1380  GOTO 1430                                         !IF SET, CONTINUE
1390  MAT M=Q                                           !STORE FIRST MAGNITUDE SWEEP
1400  MAT N=R                                           !STORE FIRST PHASE SWEEP
1410  Re=1                                              !SET ERROR RUN "ONCE THROUGH" FLAG
1420  GOTO 1070                                         !GO TO TAKE SECOND SWEEP
1430  MAT B=Q                                           !THE MAGNITUDE ARRAY, B, IS
```

```
1440                                                ! NOW CALIBRATED
1450    MAT C=R                                     !THE PHASE ARRAY, C, IS
1460                                                ! NOW CALIBRATED
1470    PRINT "MAGNITUDE,dB:"
1480    MAT PRINT B                                 !PRINT MAGNITUDE ARRAY
1490    PRINT "PHASE,deg:"
1500    MAT PRINT C                                 !PRINT PHASE ARRAY
1510    INPUT "Do you want a print-out of these ?",X$
1520    IF X$="N" THEN GOTO 1800
1530    IF X$="Y" THEN GOTO 1540
1540    PRINTER IS 0                                !RE-DEFINES THE PRINTER AS THE
1550                                                ! 9834B PAPER PRINTER
1560    ! CHECK THE S PARAMETER FLAGS
1570    Y=(S=1)
1580    IF Y THEN PRINT "S21"
1590    Y=(S=2)
1600    IF Y THEN PRINT "S12"
1610    Y=(S=3)
1620    IF Y THEN PRINT "S21"
1630    Y=(S=4)
1640    IF Y THEN PRINT "S22"
1650    Y=(Rp=1)                                    !CHECK THE ERROR RUN
1660                                                ! "PRINT/PLOT" FLAG
1670    IF Y THEN PRINT "DUAL SWEEP ERROR"
1680    PRINT "MAGNITUDE,dB:"
1690    PRINT " "
1700    MAT PRINT B
1710    PRINT "  "
1720    Y=(Rp=1)                                    !CHECK THE ERROR RUN
1730                                                ! "PRINT/PLOT" FLAG
1740    IF Y THEN PRINT "DUAL SWEEP ERROR"
1750    PRINT "PHASE,deg.:"
1760    PRINT " "
1770    MAT PRINT C
1780    PRINT IS 16                                 !REDEFINES THE PRINTER TO
1790                                                ! BE THE 9845B SCREEN
1800    INPUT "Do you want a normalized plot of these? Y or N then CONT.",X$
1810    IF X$="Y" THEN GOTO 1920
1820    IF X$="N" THEN GOTO 1830
1830    Y=(Rp=1)                                    !CHECK THE ERROR RUN
1840                                                ! "PRINT/PLOT" FLAG
1850    IF Y THEN RETURN                            !IF SET, RETURN TO CONTINUE WITH
1860                                                ! NEXT S PARAMETER
1870    Y=(E=0)                                     !CHECK THE ERROR RUN FLAG
1880    IF Y THEN RETURN                            !IF NOT SET, RETURN TO CONTINUE
1890                                                ! WITH NEXT S PARAMETER
1900    GOTO 2130                                   !ELSE, GO TO FIND ERROR BETWEEN
1910                                                ! THE TWO SWEEPS
1920    ! NOW PREPARE TO GO TO PLOTTING SUBROUTINE
1930    MAT A=B                                     !ENTER MAGNITUDE ARRAY, B, INTO
1940                                                ! PLOT ARRAY, A
1950    R=0                                         !PRESET PLOT "ONCE THROUGH" FLAG
1960    Xmin=Afreq                                  !DEFINES MINIMUM FREQUENCY FOR THE
1970                                                ! LOWER END OF THE HORIZONTAL AXIS
1980    Xmax=Bfreq                                  !DEFINES MAXIMUM FREQUENCY FOR THE
1990                                                ! UPPER END OF THE HORIZONTAL AXIS
2000    Imin=1                                      !DEFINES MINIMUM AMPLITUDE FOR THE
2010                                                ! LOWER END OF THE VERTICAL AXIS
2020    Imax=N                                      !DEFINES MAXIMUM AMPLITUDE FOR THE
2030                                                ! UPPER END OF THE VERTICAL AXIS
2040    GOSUB Max_min                               !GO TO THE Max_min SUBROUTINE
2050                                                ! WHICH FINDS Imax AND Imin
2060    GOSUB Plot                                  !GO TO THE Plot SUBROUTINE
2070    Y=(R=1)                                     !CHECK THE PLOT "ONCE THROUGH" FLAG
2080    IF Y THEN GOTO 2100                         !IF SET, CONTINUE
2090    GOTO 2300                                   !ELSE, GOTO PLOT ARRAY C
2100    Y=(E=1)                                     !CHECK ERROR RUN FLAG
2110    IF Y THEN GOTO 2130                         !IF SET, CONTINUE
2120    RETURN                                      !ELSE, RETURN
2130    Y=(Rp=1)                                    !CHECK ERROR RUN "PRINT/PLOT" FLAG
2140    IF Y THEN GOTO 2120                         !IF SET, GO TO RETURN COMMAND
2150    MAT B=M-B                                   !ELSE, SUBTRACT (dB) THE SECOND
```

```
2160                                            ! SWEEP FROM THE FIRST; MAGNITUDE
2170    MAT C=N-C                               !SUBTRACT (DEGREES) THE SECOND
2180                                            ! SWEEP FROM THE FIRST; PHASE
2190    MAT E=C                                 !LOAD PHASE ERROR ARRAY, C
2200    GOSUB 12480                             !GO TO CHECK FOR 360 DEGREE SHIFT
2210    MAT C=E                                 !RELOAD PHASE ERROR ARRAY, C, WITH
2220                                            ! CORRECTED PHASE ARRAY,E
2230    PRINT "DUAL SWEEP MAGNITUDE ERROR, dB"
2240    WAIT 2000
2250    MAT PRINT B
2260    PRINT "DUAL SWEEP PHASE ERROR, DEGREES"
2270    MAT PRINT C
2280    Rp=1                                    !SET ERROR RUN "PRINT/PLOT" FLAG
2290    GOTO 1510                               !GOTO OFFER PRINT-OUT OF THE ERRORS
2300    MAT A=C                                 !ELSE, ENTER PHASE ARRAY, C, INTO
2310                                            ! PLOT ARRAY, A
2320    R=1                                     !SET PLOT "ONCE THROUGH" FLAG
2330    GOTO 1960                               !GO TO PLOT AGAIN
2340    !
2350    ! THIS SECTION (FROM "DEFINE N") MEASURES THE HP 3577A SCREEN VALUE
2360    ! FOR EACH DATA POINT
2370    Re=0                                    !PRESET ERROR RUN "ONCE
2380                                            ! THROUGH" FLAG
2390    Rp=0                                    !PRESET ERROR RUN "PRINT/PLOT"
2400                                            ! FLAG
2410    DISP "Please wait. Measurements are being taken."
2420    OUTPUT 711;"ST5;"                       !SET SWEEP TYPE TO CONTINUOUS WAVE
2430    Xmin=Afreq                              !DEFINES MINIMUM FREQUENCY FOR THE
2440                                            ! LOWER END OF THE HORIZONTAL AXIS
2450                                            ! (AND SAVES ORIGINAL VALUE)
2460    FOR I=1 TO N
2470        OUTPUT 711 USING 2480;Afreq
2480        IMAGE "SFR;",DDD.DDDDDD,"MHZ;"      !SOURCE FREQUENCY STARTS AT
2490                                            ! DEFINED START FREQUENCY AND
2500                                            ! IS ACCURATE TO THE HERTZ
2510        OUTPUT 711;"TKM;FM1;DM1;"           !TAKE MEASUREMENT, PUT IN ASCII
2520                                            ! FORM, AND DUMP THE MARKER FROM
2530                                            ! TRACE 1 (MAGNITUDE)
2540        ENTER 711;B(I)                      !ENTER DATA INTO MAGNITUDE ARRAY, B
2550        OUTPUT 711;"TKM;FM1;DM2;"           !TAKE MEASUREMENT, PUT IN ASCII
2560                                            ! FORM AND DUMP THE MARKER FROM
2570                                            ! TRACE 2 (PHASE)
2580        ENTER 711;C(I)                      !ENTER DATA INTO PHASE ARRAY, C
2590        Afreq=Afreq+Df                      !INCREMENT FREQUENCY BY THE DELTA
2600                                            ! FREQUENCY.THIS WAS CALCULATED
2610                                            ! WHEN THE VALUE OF N WAS DEFINED
2620    NEXT I                                  !ELSE, CONTINUE
2630    Afreq=Xmin                              !RESET START FREQUENCY
2640    MAT D=B                                 !IN PREPARATION FOR MATH, LOAD
2650                                            ! MAGNITUDE ARRAY, B, INTO ARRAY D
2660    MAT E=C                                 !AND PHASE ARRAY, C, INTO ARRAY E
2670    Y=(S=3)                                 !CHECK THE S11 FLAG
2680    IF Y THEN GOTO 2730                     !IF SET, SKIP THE FOLLOWING TWO
2690                                            ! LINES OF MATH
2700    MAT Q=D-Dn                              !SUBTRACT (dB) CALIBRATION ARRAY
2710    MAT R=E-En                              !SUBTRACT (PHASE) CALIBRATION ARRAY
2720    GOTO 2760                               !GO TO CHECK FOR PHASE SHIFT
2730    GOSUB 11900                             !GO TO THE END OF ONE PART FULL
2740                                            ! CALIBRATION SUBROUTINE TO FIND
2750                                            ! THE CALIBRATED MEASUREMENT
2760    MAT E=R                                 !LOAD CALIBRATED PHASE ARRAY, R
2770                                            ! INTO ARRAY E
2780    GOSUB 12480                             !GO TO CHECK FOR 360 DEGREE
2790                                            ! PHASE SHIFT
2800    MAT R=E                                 !RELOAD ARRAY R WITH CORRECTED
2810                                            ! PHASE ARRAY
2820    Y=(E=1)                                 !CHECK ERROR RUN FLAG
2830    IF Y THEN GOTO 2850                     !IF SET, CONTINUE
2840    GOTO 2920                               !ELSE, GO TO LOAD ARRAYS B AND C
2850    Y=(Re=0)                                !CHECK ERROR RUN "ONCE THROUGH" FLAG
2860    IF Y THEN GOTO 2880                     !IF NOT SET GO TO STORE FIRST SWEEP
2870    GOTO 2920                               !IF SET, CONTINUE
```

```
2880    MAT M=Q                                          !STORE FIRST MAGNITUDE SWEEP
2890    MAT N=R                                          !STORE FIRST PHASE SWEEP
2900    Re=1                                             !SET ERROR RUN "ONCE THROUGH" FLAG
2910    GOTO 2410                                        !GO TO TAKE SECOND SWEEP
2920    MAT B=Q                                          !MAGNITUDE ARRAY, B, IS NOW
2930                                                     ! CALIBRATED
2940    MAT C=R                                          !PHASE ARRAY, C, IS NOW CALIBRATED
2950    PRINT "MAGNITUDE,dB:"
2960    MAT PRINT B                                      !PRINT THE MAGNITUDE ARRAY
2970    PRINT "PHASE,deg:"
2980    MAT PRINT C                                      !PRINT THE PHASE ARRAY
2990    INPUT "Do you want a print-out of these?",X$
3000    IF X$="N" THEN GOTO 3280
3010    IF X$="Y" THEN GOTO 3020
3020    PRINTER IS 0                                     !REDEFINE THE PRINTER TO
3030                                                     ! PRINT ON THE 9845B PAPER
3040    ! CHECK THE S PARAMETER FLAGS
3050    Y=(S=1)
3060    IF Y THEN PRINT "S21"
3070    Y=(S=2)
3080    IF Y THEN PRINT "S12"
3090    Y=(S=3)
3100    IF Y THEN PRINT "S11"
3110    Y=(S=4)
3120    IF Y THEN PRINT "S22"
3130    Y=(Rp=1)                                         !CHECK THE ERROR RUN
3140                                                     ! "PRINT/PLOT" FLAG
3150    IF Y THEN PRINT "DUAL SWEEP ERROR"
3160    PRINT "MAGNITUDE,dB:"
3170    PRINT " "
3180    MAT PRINT B                                      !PRINT MAGNITUDE ARRAY
3190    PRINT "  "
3200    Y=(Rp=1)                                         !CHECK THE ERROR RUN
3210                                                     ! "PRINT/PLOT" FLAG
3220    IF Y THEN PRINT "DUAL SWEEP ERROR"
3230    PRINT "PHASE,deg:"
3240    PRINT " "
3250    MAT PRINT C                                      !PRINT PHASE ARRAY
3260    PRINTER IS 16                                    !REDEFINE THE PRINTER TO BE
3270                                                     ! THE 9845B SCREEN
3280    INPUT "Do you want a normalized plot of these? Y or N then CONT.",X$
3290    IF X$="Y" THEN GOTO 3390
3300    IF X$="N" THEN GOTO 3310
3310    Y=(Rp=1)                                         !CHECK ERROR RUN "PRINT/PLOT" FLAG
3320    IF Y THEN RETURN                                 !IF SET, RETURN TO CONTINUE WITH
3330                                                     ! THE NEXT S PARAMETER
3340    Y=(E=0)                                          !CHECK THE ERROR RUN FLAG
3350    IF Y THEN RETURN                                 !IF NOT SET, RETURN T CONTINUE
3360                                                     ! WITH THE NEXT S PARAMETER
3370    GOTO 3610                                        !ELSE GO TO FIND THE ERROR
3380                                                     ! IN THE TWO SWEEPS
3390    ! PREPARE TO GO TO PLOTTING SUBROUTINE
3400    R=0                                              !PRESET PLOT "ONCE THROUGH" FLAG
3410    MAT A=B                                          !ENTER MAGNITUDE ARRAY, B, INTO
3420                                                     ! PLOT ARRAY, A
3430    Xmin=Afreq                                       !DEFINES MINIMUM FREQUENCY FOR THE
3440                                                     ! LOWER END OF HORIZONTAL AXIS
3450    Xmax=Bfreq                                       !DEFINES MAXIMUM FREQUENCY FOR THE
3460                                                     ! UPPER END OF THE HORIZONTAL AXIS
3470    Imin=1                                           !DEFINES MINIMUM AMPLITUDE FOR THE
3480                                                     ! LOWER END OF THE VERTICAL AXIS
3490    Imax=N                                           !DEFINES MAXIMUM AMPLITUDE FOR THE
3500                                                     !UPPER END OF THE VERTICAL AXIS
3510    GOSUB Max_min                                    !GO TO THE Max_min SUBROUTINE
3520                                                     ! TO FIND Imax AND Imin
3530    GOSUB Plot                                       !GO TO THE Plot SUBROUTINE
3540    Y=(R=1)                                          !CHECK THE PLOT "ONCE THROUGH" FLAG
3550    IF Y THEN GOTO 3570                              !IF SET, CONTINUE
3560    GOTO 3780                                        !ELSE, GO TO PLOT PHASE ARRAY, C
3570    Y=(E=1)                                          !CHECK ERROR RUN FLAG
3580    IF Y THEN GOTO 3610                              !IF SET, CONTINUE
3590    RETURN                                           !ELSE, RETURN TO CONTINUE WITH
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```
3600                                              ! THE NEXT S PARAMETER
3610  Y=(Rp=1)                                    !CHECK ERROR RUN "PRINT/PLOT" FLAG
3620  IF Y THEN GOTO 3590                         !IF SET, GO TO RETURN COMMAND
3630  MAT B=M-B                                   !SUBTRACT (dB) THE SECOND MAGNITUDE
3640                                              ! SWEEP FROM THE FIRST
3650  MAT C=N-C                                   !SUBTRACT (DEGREES) THE SECOND
3660                                              ! PHASE SWEEP FROM THE FIRST
3670  MAT E=C                                     !LOAD PHASE ERROR ARRAY, C
3680  GOSUB 12480                                 !GO TO CHECK FOR 360 DEGREE SHIFT
3690  MAT C=E                                     !RELOAD PHASE ERROR ARRAY, C, WITH
3700                                              ! CORRECTED PHASE ARRAY, E
3710  PRINT "DUAL SWEEP MAGNITUDE ERROR, dB"
3720  WAIT 2000
3730  MAT PRINT B
3740  PRINT "DUAL SWEEP PHASE ERROR, DEGREES"
3750  MAT PRINT C
3760  Rp=1                                        !SET ERROR RUN "PRINT/PLOT" FLAG
3770  GOTO 2990                                   !GO TO OFFER PRINT-OUT OF ERRORS
3780  MAT A=C                                     !ELSE, ENTER MAGNITUDE ARRAY, C,
3790                                              ! INTO PLOT ARRAY, A
3800  R=1                                         !SET PLOT "ONCE THROUGH" FLAG
3810  GOTO 3430                                   !GO TO PLOT AGAIN
3820  !
3830  ! THIS SECTION (FROM"DEFINE Df") MEASURES THE HP3577A VALUE FOR EACH
3840  ! DATA POINT (THE NUMBER OF DATA POINTS HAS BEEN CALCULATED FROM THE
3850  ! DEFINED DELTA FREQUENCY)
3860  Re=0                                        !PRESET ERROR RUN "ONCE
3870                                              ! THROUGH" FLAG
3880  Rp=0                                        !PRESET ERROR RUN "PRINT/PLOT"
3890                                              ! FLAG
3900  DISP "Please wait. Measurements are being taken."
3910  OUTPUT 711;"ST5;"                           !SWEEP TYPE SET TO CONTINUOUS WAVE
3920  Xmin=Cfreq                                  !DEFINES MINIMUM FREQUENCY FOR THE
3930                                              ! LOWER END F THE HORIZONTAL AXIS
3940                                              ! (AND SAVES THE VALUE FOR THE
3950                                              ! START OF THE BANDWIDTH)
3960  FOR I=Ii TO N                               !IF SAW DEVICE, LOOP BEGINS WITH
3970                                              ! 2. OTHERWISE, LOOP BEGINS WITH 1
3980       Cfreq=(I-1)*Df+Xmin                    !INCREMENT FREQUENCY BY THE
3990                                              ! DELTA FREQUENCY
4000       OUTPUT 711 USING 4010;Cfreq
4010       IMAGE "SFR;",DDD.DDDDDD,"MHz;"         !SOURCE FREQUENCY STARTS AT MINIMUM
4020                                              ! VALUE OF THE BAND AND IS
4030                                              ! ACCURATE TO ONE HERTZ
4040       OUTPUT 711;"TKM;FM1;DM1;"              !TAKE MEASUREMENT, PUT IN ASCII
4050                                              ! FORM, AND DUMP THE MAGNITUDE
4060                                              ! MARKER FROM TRACE1
4070       ENTER 711;B(I)                         !ENTER DATA INTO MAGNITUDE ARRAY, B
4080       OUTPUT 711;"TKM;FM1;DM2"               !TAKE MEASUREMENT, PUT IN ASCII
4090                                              ! FORM, AND DUMP THE PHASE
4100                                              ! MARKER FROM TRACE 2
4110       ENTER 711;C(I)                         !ENTER DATA INTO THE PHASE ARRAY, C
4120  NEXT I
4130  Cfreq=Xmin                                  !RESTORE Cfreq TO IT'S
4140                                              ! DEFINED VALUE
4150  MAT D=B                                     !IN PREPARATION FOR MATH, LOAD
4160                                              ! MAGNITUDE ARRAY, B, INTO ARRAY D
4170  MAT E=C                                     !AND PHASE ARRAY, C, INTO ARRAY E
4180  Y=(S=3)                                     !CHECK THE S11 FLAG
4190  IF Y THEN GOTO 4240                         !IF SET, THE FOLLOWING MATH IS
4200                                              ! NOT NECESSARY
4210  MAT Q=D-Dn                                  !SUBTRACT (dB) CALIBRATION ARRAY
4220  MAT R=E-En                                  !SUBTRACT (PHASE) CALIBRATION ARRAY
4230  GOTO 4270                                   !GO TO CHECK FOR PHASE SHIFT
4240  GOSUB 11900                                 !GO TO THE END OF ONE PORT FULL
4250                                              ! CALIBRATION SUBROUTINE TO FIND
4260                                              ! THE CALIBRATED VALUES
4270  MAT E=R                                     !LOAD PHASE ARRAY, R, INTO ARRAY E
4280  GOSUB 12480                                 !GO TO CHECK FOR 360 DEGREE SHIFT
4290  MAT R=E                                     !RELOAD PHASE ARRAY, R, WITH
4390                                              ! CORRECTED VALUES
4310  Y=(E=1)                                     !CHECK ERROR RUN FLAG
```

```
4320  IF Y THEN GOTO 4340                       !IF SET, CONTINUE
4330  GOTO 4420                                 !ELSE, GO TO LOAD ARRAYS B AND C
4340  Y=(Re=0)                                  !CHECK ERROR RUN "ONCE THROUGH" FLAG
4350  IF Y THEN GOTO 4380                       !IF NOT SET, GO TO STORE FIRST
4360                                            ! ERROR SWEEP
4370  GOTO 4420                                 !IF SET, CONTINUE
4380  MAT M=Q                                   !STORE FIRST MAGNITUDE SWEEP
4390  MAT N=R                                   !STORE FIRST PHASE SWEEP
4400  Re=1                                      !SET ERROR RUN "ONCE THROUGH FLAG
4410  GOTO 3900                                 !GO TO TAKE SECOND SWEEP
4420  MAT B=Q                                   !MAGNITUDE ARRAY , B, IS NOW
4430                                            ! CALIBRATED
4440  MAT C=R                                   !PHASE ARRAY, C, IS NOW CALIBRATED
4450  PRINT "MAGNITUDE,dB:"
4460  MAT PRINT B                               !PRINT THE MAGNITUDE ARRAY
4470  PRINT "  "
4480  PRINT "PHASE,deg:"
4490  MAT PRINT C                               !PRINT THE PHASE ARRAY
4500  INPUT "Do you want a print-out of these?",X$
4510  IF X$="N" THEN GOTO 4790
4520  IF X$="Y" THEN GOTO 4530
4530  PRINTER IS 0                              !REDEFINE THE PRINTER TO PRINT
4540                                            ! OUT ON 9845B PAPER
4550  ! CHECK THE S PARAMETER FLAGS
4560  Y=(S=1)
4570  IF Y THEN PRINT "S21"
4580  Y=(S=2)
4590  IF Y THEN PRINT "S12"
4600  Y=(S=3)
4610  IF Y THEN PRINT "S11"
4620  Y=(S=4)
4630  IF Y THEN PRINT "S22"
4640  Y=(Rp=1)                                  !CHECK THE ERROR RUN
4650                                            ! "PRINT/PLOT" FLAG
4660  IF Y THEN PRINT "DUAL SWEEP ERROR"
4670  PRINT "MAGNITUDE,dB:"
4680  PRINT " "
4690  MAT PRINT B                               !PRINT MAGNITUDE ARRAY
4700  PRINT "  "
4710  Y=(Rp=1)                                  !CHECK THE ERROR RUN
4720                                            ! "PRINT/PLOT" FLAG
4730  IF Y THEN PRINT "DUAL SWEEP ERROR"
4740  PRINT "PHASE,deg:"
4750  PRINT " "
4760  MAT PRINT C                               !PRINT PHASE ARRAY
4770  PRINTER IS 16                             !REDEFINE THE PRINTER TO BE
4780                                            ! THE 9845B SCREEN
4790  GOSUB 12610                               !GO TO OFFER TO SAVE RESULTS
4800  INPUT "Do you want a normalized plot of these? Y or N then CONT.",X$
4810  IF X$="Y" THEN GOTO 4910
4820  IF X$="N" THEN GOTO 4830
4830  Y=(Rp=1)                                  !CHECK THE ERROR RUN
4840                                            ! "PRINT/PLOT" FLAG
4850  IF Y THEN RETURN                          !IF SET, THEN RETURN TO CONTINUE
4860                                            ! WITH THE NEXT S PARAMETER
4870  Y=(E=0)                                   !CHECK THE ERROR RUN FLAG
4880  IF Y THEN RETURN                          !IF NOT SET, RETURN TO CONTINUE
4890                                            ! WITH THE NEXT S PARAMETER
4900  GOTO 5120                                 !ELSE, GO TO FIND ERROR
4910  ! PREPARE TO GO TO PLOTTING SUBROUTINE
4920  R=0                                       !PRESET THE PLOT "ONCE
4930                                            ! THROUGH" FLAG TO ZERO
4940  MAT A=B                                   !ENTER MAGNITUDE ARRAY, B,
4950                                            ! INTO PLOT ARRAY, A
4960  Xmax=Dfreq                                !DEFINES MAXIMUM FREQUENCY FOR THE
4970                                            ! UPPER END OF THE HORIZONTAL AXIS
4980  Imin=1                                    !DEFINES MINIMUM AMPLITUDE FOR THE
4990                                            ! LOWER END OF THE VERTICAL AXIS
```

```
5000    Imax=X                                       !DEFINES MAXIMUM AMPLITUDE FOR THE
5010                                                 ! UPPER END OF THE VERTICAL AXIS
5020    GOSUB Max_min                                !GO TO Max_min SUBROUTINE TO
5030                                                 ! FIND Imax AND Imin
5040    GOSUB Plot                                   !GO TO THE Plot SUBROUTINE
5050    Y=(R=1)                                      !CHECK THE PLOT "ONCE THROUGH" FLAG
5060    IF Y THEN GOTO 5080                          !IF SET, CONTINUE
5070    GOTO 5300                                    !ELSE, GO TO PLOT PHASE ARRAY, C
5080    Y=(E=1)                                      !CHECK ERROR RUN FLAG
5090    IF Y THEN GOTO 5120                          !IF SET, GO TO FIND ERROR
5100    RETURN                                       !ELSE, RETURN TO CONTINUE WITH
5110                                                 ! THE NEXT S PARAMETER
5120    Y=(Rp=1)                                     !CHECK ERROR RUN "PRINT/PLOT" FLAG
5130    IF Y THEN GOTO 5100                          !IF SET, THEN RETURN TO CONTINUE
5140                                                 ! WITH THE NEXT S PARAMETER
5150    MAT B=M-B                                    !SUBTRACT (dB) THE SECOND MAGNITUDE
5160                                                 ! SWEEP FROM THE FIRST
5170    MAT C=N-C                                    !SUBTRACT (DEGREES) THE SECOND
5180                                                 ! PHASE SWEEP FROM THE FIRST
5190    MAT E=C                                      !LOAD PHASE ERROR ARRAY, C
5200    GOSUB 12480                                  !GO TO CHECK FOR 360 SHIFT
5210    MAT C=E                                      !RELOAD PHASE ERROR ARRAY, C, WITH
5220                                                 ! CORRECTED PHASE ARRAY,E
5230    PRINT "DUAL SWEEP MAGNITUDE ERROR, dB"
5240    WAIT 2000
5250    MAT PRINT B
5260    PRINT "DUAL SWEEP PHASE ERROR, DEGREES"
5270    MAT PRINT C                                  !SET ERROR RUN "PRINT/PLOT" FLAG
5280    Rp=1                                         ! GO TO OFFER PRINT-OUT OF ERROR
5290    GOTO 4500                                    !ELSE, ENTER PHASE ARRAY, C, INTO
5300    MAT A=C                                      ! PLOT ARRAY, A
5310                                                 !SET THE PLOT "ONCE THROUGH" FLAG
5320    R=1                                          !GO TO PLOT PHASE
5330    GOTO 4960                                    !RETURN TO CONTINUE WITH THE
5340    RETURN                                       ! NEXT S PARAMETER
5350
5360    !
5370    ! CARL BISHOP'S PLOTTING SUBROUTINE ADDED HERE
5380    !
5390    ! BASIC SUBROUTINE PACKAGE, REV. A, 6/16/83
5400    ! UNIVERSITY OF CENTRAL FLORIDA
5410    ! COLLEGE OF ENGINEERING, ELECTRICAL ENGINEERING DEPARTMENT
5420    ! CARLTON BISHOP
5430 Plot:!
5440    X1=(Xmin-Xmax)/2
5450    X$="FREQUENCY, MHZ"
5460    IF ABS(X1)>10 THEN GOTO 5490
5470    X1=X1*1000
5480    X$="FREQUENCY, KHZ"
5490    X2=ABS(X1/5)
5500    Xtic=(Xmax-Xmin)/10
5510    Ytic=(Ymax-Ymin)/10
5520    Delta_x=(Xmax-Xmin)/(Imax-1)
5530    SETGU                                        !Use graphics units to labe plot
5540    ! HERE SLD HAS ADDED AN OPTION TO PLOT ON THE 9845B SCREEN OR
5550    ! PLOT ON THE 7475A PLOTTER. CARL'S PROGRAM DEFINES PLOTTER
5560    ! AS "GRAPHICS"
5570    Sa=0                                         !PRESET THE "BOTH FLAG TO ZERO
5580    T=0                                          !PRESET "ONCE THROUGH" FLAG TO ZERO
5590    INPUT "Plot on this screen S, plotter, P, or both, B?",P$
5600    DISP "Press CONT. when each plot is finished."
5610    WAIT 4000
5620    IF P$="S" THEN GOTO 5660
5630    IF P$="P" THEN GOTO 5680
5640    IF P$="B" THEN GOTO 5650
5650    Sa=1                                         !SET THE "BOTH" FLAG
5660    PLOTTER IS "GRAPHICS"                        !Define 9845B as plotting device
5670    GOTO 5700
5680    PLOTTER IS "9872A"                           !DEFINE 7475A AS PLOTTING DEVICE
5690    INPUT "Is there paper in the plotter? Press CONT.",Y
5700    GRAPHICS
5710    LINE TYPE 1                                  !Use solid line for plotting
```

```
5720   LOCATE 18,121.9,14.3,92.7                          !Position graph on the paper
5730   CLIP 18,121.9,14.3,92.7
5740   PEN 1                                              !Use left pen for plotting
5750   FRAME                                              !Draw border of graph
5760   CSIZE 2.5,.5                                       !Set the size of the characters
5770   MOVE 12.1,11.3                                     !Pen in position to scale X axis
5780   FOR I=1 TO 11
5790   Ti=X2*(I-1)+X1                                     !Calculate value of tic mark
5800   LABEL USING "SDDDD.D";Ti                           !Put it on the graph
5810   IPLOT 10.6,2.5,2                                   !Position for next tic mark
5820   NEXT I
5830   MOVE 6.6,13.9                                      !Pen in position to scale Y axis
5840   FOR I=1 TO 11
5850   Ti=Ytic*(I-1)+Ymin                                 !Calculate value of tic mark
5860   LABEL USING "SDDDD.DD";Ti                          !Put it on the graph
5870   IPLOT 0,10.29,2                                    !Position for next tic mark
5880   NEXT I
5890   LDIR 0
5900   LORG 4
5910   MOVE 70.1,7.8                                      !Put pen position to labe X axis
5920   LABEL USING "#,K";X$                               !Label X axis
5930   MOVE 70.1,2.8
5940   LABEL USING "#,K,DDD.DDDDDD,K";"Fo= ",(Xmax+Xmin)/2," MHZ"
5950   MOVE 7.5,53.5                                      !Pen in position to label Y axis
5960   LDIR PI/2                                          !Label bottom to top
5970   Y=(E=1)                                            !CHECK ERROR RUN FLAG
5980   IF Y THEN GOTO 6000                                !IF SET, GO TO CHECK ANOTHER FLAG
5990   GOTO 6090                                          !ELSE, CONTINUE
6000   Y=(Rp=0)
6010   IF Y THEN GOTO 6090
6020   Y=(R=0)                                            !CHECK PLOT "ONCE THROUGH" FLAG
6030   IF Y THEN GOTO 6050
6040   GOTO 6070
6050   Y$="MAG. ERROR, dB"
6060   GOTO 6150
6070   Y$="PHASE ERROR, DEG"
6080   GOTO 6150                                          !GO TO LABEL Y AXIS
6090   Y=(R=0)                                            !CHECK PLOT "ONCE THROUGH" FLAG
6100   IF Y THEN GOTO 6120
6110   GOTO 6140
6120   Y$="MAGNITUDE, dB"
6130   GOTO 6150
6140   Y$="PHASE, DEGREES"
6150   LABEL USING "#,K";Y$
6160   CSIZE 4,.5                                         !Make Heading of the graph larger
6170   MOVE 70.1,96.2                                     !Position at top to print heading
6180   LDIR 0                                             !Print it left to right
6190   Y=(S=1)                                            !CHECK S21 FLAG
6200   IF Y THEN H$="S21"                                 !IF SET, HEADING = S21
6210   Y=(S=2)                                            !CHECK S12 FLAG
6220   IF Y THEN H$="S12"                                 !IF SET, HEADING = S12
6230   Y=(S=3)                                            !CHECK S11 FLAG
6240   IF Y THEN H$="S11"                                 !IF SET, HEADING = S11
6250   Y=(S=4)                                            !CHECK S22 FLAG
6260   IF Y THEN H$="S22"                                 !IF SET, HEADING =S22
6270   LABEL USING "#,K";H$
6280   SCALE Xmin,Xmax,Ymin,Ymax                          !Set user scale according to data
6290   SETUU                                              !Return to user defined units
6300   AXES Xtic,Ytic,Xmin,Ymin
6310   MOVE Xmin,Ymin                                     !Start plot at first point
6320   FOR I=Imin TO Imax
6330   DRAW Xmin+(I-1)*Delta_x,A(I)
6340   NEXT I
6350   PEN 0
6360   PAUSE
6370   EXIT GRAPHICS
6380   Y=(Sa*T)=1)                                        !CHECK TO SEE IF "BOTH" FLAG AND
6390                                                      ! "ONCE THROUGH" FLAG ARE SET
6400   IF Y THEN GOTO 6450                                !IF SO, RETURN TO MAIN PLOT/PRINT
6410                                                      ! SUBROUTINE
6420   T=1                                                !SET THE "ONCE THROUGH" FLAG
6430   Y=(Sa=1)                                           !CHECK TO SEE IF "BOTH" FLAG IS SET
```

```
6440    IF Y THEN GOTO 5680                              !IF SO, NOW PLOT ON 7475A PLOTTER
6450    RETURN
6460 Max_min:                                            ! Find maximum and minimum values
6470    Ymin=1E99
6480    Ymax=-1E99
6490    FOR I=Imin TO Imax
6500    IF A(I)>Ymax THEN Ymax=A(I)
6510    IF A(I)<Ymin THEN Ymin=A(I)
6520    NEXT I
6530    RETURN
6540    !
6550    ! POLAR-TO-REAL-AND-IMAGINARY SUBROUTINE (DEGREES)
6560    ! THIS SUBROUTINE CHANGES POLAR VALUES TO REAL AND IMAGINARY
6570    ! VALUES IN PREPARATION FOR LINEAR MATHEMATICAL OPERATIONS. THE
6580    ! MAGNITUDE COMING IN IS LINEAR.  THE PHASE COMING IN IS IN DEGREES.
6590    FOR Z=1 TO N
6600        A=D(Z)                                       !MAGNITUDE
6610        C=E(Z)*PI/180                                !CHANGE PHASE ARRAY, E, TO RADIANS
6620        RAD                                          !SET RADIAN MODE
6630        F=A*COS(C)                                   !FINDING REAL PART OF ARRAYS D
6640                                                     ! AND E
6650        P(Z)=F                                       !REAL PART OF ARRAY D AND E
6660        G=A*SIN(C)                                   !FINDING IMAGINARY PART OF ARRAYS
6670                                                     ! D AND E
6680        O(Z)=G                                       !IMAGINARY PART OF ARRAYS D AND E
6690    NEXT Z
6700    RETURN
6710    !
6720    ! POLAR-TO-REAL-AND-IMAGINARY SUBROUTINE (RADIANS)
6730    ! THIS SUBROUTINE CHANGES POLAR VALUES TO REAL AND IMAGINARY
6740    ! VALUES IN PREPARATION FOR LINEAR MATHEMATICAL OPERATION.  THE
6750    ! MAGNITUDE COMING IN IS IN LOG FORM.  THE PHASE COMING IN IS IN RADIANS.
6760    FOR Z=1 TO N
6770        A=10^D(Z)                                    !MAGNITUDE
6780        C=E(Z)                                       !PHASE ARRAY (RADIANS)
6790        RAD                                          !SET RADIAN MODE
6800        F=A*COS(C)                                   !FINDING REAL PART OF ARRAYS D
6810                                                     ! AND E
6820        P(Z)=F                                       !REAL PART OF ARRAYS D AND E
6830        G=A*SIN(C)                                   !FINDING IMAGINARY PART OF ARRAYS
6840                                                     ! D AND E
6850        O(Z)=G                                       !IMAGINARY PART OF ARRAYS D AND E
6860    NEXT Z
6870    RETURN
6880    !
6890    ! REAL-AND-IMAGINARY-TO-POLAR SUBROUTINE
6900    ! THIS SUBROUTINE CHANGES REAL AND IMAGINARY VALUES TO POLAR (LOG
6910    ! MAGNITUDE VALUES)
6920    FOR Z=1 TO N
6930        A=SQR(P(Z)^2+O(Z)^2)                         !RETURNING TO POLAR (MAGNITUDE)
6940        B=LGT(A)                                     !RETURNING MAGNITUDE TO LOG
6950        D(Z)=B                                       !MAGNITUDE IN POLAR FORM, LOG
6960        RAD                                          !SET RADIAN MODE
6970        Y=(O(Z)>=0)                                  !NEXT FEW LINES CHECK PHASE
6980        IF Y THEN GOTO 7020                          !QUADRANT IN PREPARATION FOR THE
6990        Y=(P(Z)<0)                                   !ARCTANGENT OPERATION
7000        IF Y THEN GOTO 7060
7010        GOTO 7040
7020        Y=(P(Z)<0)
7030        IF Y THEN GOTO 7060
7040        C=0
7050        GOTO 7070
7060        C=PI
7070        C=C+ATN(O(Z)/P(Z))                           !RETURNING TO POLAR (PHASE)
7080        E(Z)=C                                       !PHASE IN POLAR FORM (RADIANS)
7090    NEXT Z
7100    RETURN
7110    !
7120    ! DATA ACQUISITION MEHTOD SUBROUTINE
7130    ! THIS SUBROUTINE ALLOWS THE USER TO CHOOSE WHICH METHOD OF
7140    ! DATA ACQUISITION HE WOULD LIKE
7150    Du=0                                             !PRESET "DUMP THE SCREEN" FLAG
```

```
7160   Nu=0                                           !PRESET "DEFINE N" FLAG
7170   Fr=0                                           !PRESET "DEFINE Df" FLAG
7180   DISP "You can save your results only by defining the delta frequency."
7190   WAIT 5000
7200   INPUT "Do you want to dump the screen, D, define df, F, or define N,N?",S$
7210   IF S$="D" THEN GOTO 7250
7220   IF S$="N" THEN GOTO 7320
7230   IF S$="F" THEN GOTO 7390
7250   ! THIS SECTION DUMPS THE VALUES OF THE 401 DATA POINTS FROM
7260   ! THE HP 3577A SCREEN
7270   Du=1                                           !SET THE "DUMP THE SCREEN"
7280                                                  ! FLAG TO ONE
7290   N=401                                          !DEFINE N
7291   PRINT "Your delta frequency =";(Bfreq-Afreq)/400,"MHz and N=401."
7300   RETURN
7310   !
7320   ! THIS SECTION ALLOWS THE USER TO DEFINE THE NUMBER OF DATA POINTS. THE
7330   ! DELTA FREQUENCY IS THEN CALCULATED.
7340   Nu=1                                           !SET "DEFINE N" FLAG TO ONE
7350   INPUT "N = ? (1<N>1025) Enter value and press CONT.",N
7360   Df=(Bfreq-Afreq)/(N-1)                         !CALCULATE DELTA FREQUENCY
7361   PRINT "Your delta frequency =";Df,"MHz for N =";N
7370   RETURN
7380   !
7390   ! THIS SECTION ALLOWS THE USER TO DEFINE THE DELTA FREQUENCY. THE
7400   ! NUMBER OF DATA POINTS IS CALCULATED BY N=2^A POWER AND THE NEW
7410   ! (SMALLER) DELTA FREQUENCY IS CALCULATED.
7420   Fr=1                                           !SET "DEFINE dF" FLAG
7430   INPUT "Start of bandwidth = ? Enter in MHz and press CONT.",Cfreq
7440   Y=(Cfreq>=Afreq)                               !DOES THE DESIRED BAND BEGIN
7450                                                  ! AT RO AFTER THE CALIBRATED
7460                                                  ! START FREQUENCY?
7470   IF Y THEN 7540                                 !IF SO, CONTINUE
7480                                                  ! IF NOT, ALLOW USER TO DEFINE
7490                                                  ! A NEW START OF BANDWIDTH
7500   DISP "You previously calibrated for a start frequency of ";Afreq
7510   WAIT 5000
7520   GOTO 7430                                      !GO TO ENTER NEW START OF BANDWIDTH
7530                                                  ! BANDWIDTH
7540   INPUT "End of bandwidth = ?  Enter in MHz and press CONT.",Dfreq
7550   Y=(Dfreq<=Bfreq)                               !DOES THE DESIRED BAND END
7560                                                  ! BEFORE OR AT THE CALIBRATED
7570                                                  ! STOP FREQUENCY?
7580   IF Y THEN 7650                                 !IF SO, CONTINUE
7590                                                  ! IF NOT, ALLOW USER TO DEFINE
7600                                                  ! A NEW END OF BANDWIDTH
7610   DISP "You previously calibrated for a stop frequency of";Bfreq
7620   WAIT 5000
7630   GOTO 7540                                      !GO TO ENTER NEW END OF
7640                                                  ! BANDWIDTH
7650   INPUT "Delta frequency = ?  Enter in MHz and press CONT.",Df
7660   Bw=Dfreq-Cfreq                                 !CALCULATE THE BANDWIDTH
7670   Y=(Bw>Df)                                      !IS THE DELTA FREQUENCY SMALLER
7680                                                  ! THAN THE DESIRED BANDWIDTH?
7690   IF Y THEN 7750                                 !IF SO, CONTINUE
7700                                                  ! IF NOT, ALLOW USER TO DEFINE
7710                                                  ! A NEW DELTA FREQUENCY
7720   DISP "The delta freq. must be smaller than your defined bandwidth of";Bw
7730   WAIT 5000
7740   GOTO 7650                                      !GO TO ENTER NEW DELTA FREQUENCY
7750   N=Bw/Df                                        !CALCULATES THE MINIMUM NUMBER
7760                                                  ! OF DATA POINTS NECESSARY
7770   Y=(N<1024)                                     !CHECKS N
7780   IF Y THEN GOTO 7830
7790   X=Bw/1024
7800   DISP "The delta freq. for the defined bandwidth must be >=";X
7810   WAIT 5000
7820   GOTO 7650                                      !GO TO ENTER NEW DELTA FREQUENCY
7830   A=0                                            !SETS VARIABLE A INITIALLY TO 0
7840   ! NOW CALCULATE THE NUMBER OF DATA POINTS NEEDED TO SATISFY THE
7850   ! REQUIREMENT FOR A N=2^A POINT FILE
7860   X=2^A                                          !CALCULATE NEW NUMBER OF
```

```
7870                                          ! DATA POINTS
7880   Y=(X>N)                                !IS THE NEW NUMBER OF DATA
7890                                          ! GREATER THAN OR EQUAL TO THE
7900                                          ! MINIMUM NUMBER OF DATA POINTS?
7910   IF Y THEN 7950                         !IF SO, CONTINUE
7920   A=A+1                                  !IF NOT, INCREMENT VARIABLE A AND
7930   GOTO 7860                              !RETURN TO RE-CALCULATE A NEW
7940                                          ! NUMBER OF DATA POINTS
7950   Df=Bw/X                                !CALCULATE THE NEW (AND SMALLER)
7960                                          ! DELTA FREQUENCY
7970   PRINT "Better yet, you may have a";X,"point file with Df=";Df,"MHz."
7990   DISP "Oh, happy day!!"
8000   WAIT 5000
8010   N=X                                    !REDEFINE N
8020   RETURN
8030   !
8040   ! NORMALIZING SWEEP WITH THRU/OPEN
8050   Y=(S=4)                                !CHECK FOR S22 FLAG
8060   IF Y THEN GOTO 8100                    !IF SET, CALIBRATE WITH AN "OPEN"
8070   INPUT "Replace DUT with the THRU then press CONT.",Y
8080   DISP "Please wait. Measurements are being taken."
8090   GOTO 8120                              !SKIP THE NEXT STATEMENTS
8100   INPUT "Replace DUT with the OPEN. Press CONT.",Y
8110   DISP "Please wait. Measurements are being taken."
8120   Y=(Du=1)                               !CHECK THE "DUMP THE SCREEN" FLAG
8130   IF Y THEN GOTO 8210                    !IF SET, GO TO TAKE CALIBRATION
8140                                          ! MEASUREMENTS
8150   Y=(Nu=1)                               !ELSE, CHECK "DEFINE N" FLAG
8160   IF Y THEN GOTO 8360                    !IF SET, GO TO TAKE CALIBRATION
8170                                          ! MEASUREMENTS
8180   Y=(Fr=1)                               !ELSE, CHECK "DEFINE dF" FLAG
8190   IF Y THEN GOTO 8680                    !IF SET, GO TO TAKE CALIBRATION
8200                                          ! MEASUREMENTS
8210   OUTPUT 711;"SM2;TKM;FM1;DT1;"          !SINGLE SWEEP, TAKE MEASUREMENTS,
8220                                          ! PUT IN ASCII FORM, DUMP TRACE 1
8230   ENTER 711 USING "#,F";Dn(*)            !ENTER DATA INTO THE CALIBRATION
8240                                          ! MAGNITUDE ARRAY, Dn
8250   OUTPUT 711;"SM2;TKM;FM1;DT2;"          !SINGLE SWEEP, TAKE MEASUREMENTS,
8260                                          ! PUT IN ASCII FORM, DUMP TRACE 2
8270   ENTER 711 USING "#,F";En(*)            !ENTER DATA INTO THE CALIBRATION
8280                                          ! PHASE ARRAY, En
8290   Y=(S=4)
8300   IF Y THEN GOTO 8330                    !IF SET, SKIP THE NEXT STATEMENT
8310   INPUT "Replace the THRU with the DUT. Press CONT.",Y
8320   GOTO 8340
8330   INPUT "Replace the OPEN with the DUT. Press CONT.",Y
8340   RETURN
8350   !
8360   OUTPUT 711;"ST5;"                      !SET SWEEP TYPE TO CONTINUOUS WAVE
8370   Xmin=Afreq                             !DEFINES MINIMUM FREQUENCY FOR THE
8380                                          ! LOWER END OF THE HORIZONTAL AXIS
8390                                          ! (SAVES THE VALUE OF THE START
8400                                          ! FREQUENCY)
8410   FOR I=1 TO N
8420       OUTPUT 711 USING 8430;Afreq
8430       IMAGE "SFR;",DDD.DDDDDD,"MHZ;"     !SOURCE FREQUENCY STARTS AT
8440                                          ! DEFINED START FREQUENCY AND
8450                                          ! IS ACCURATE TO ONE HERTZ
8460       OUTPUT 711;"TKM;FM1;DM1;"          !TAKE MEASUREMENT, PUT IN ASCII
8470                                          ! FORM, AND DUMP THE MAGNITUDE
8480                                          ! MARKER FROM TRACE 1
8490       ENTER 711;Dn(I)                    !ENTER DATA INTO CALIBRATION
8500                                          ! MAGNITUDE ARRAY, Dn
8510       OUTPUT 711;"TKM;FM1;DM2;"          !TAKE MEASUREMENT, PUT IN ASCII
8520                                          ! FORM, AND DUMP CALIBRATION PHASE
8530                                          ! MARKER FROM TRACE 2
8540       ENTER 711;En(I)                    !ENTER DATA INTO CALIBRATION
8550                                          ! PHASE ARRAY, En
8560       Afreq=Afreq+Df                     !INCREMENT FREQUENCY BY THE
8570                                          ! CALCULATED DELTA FREQUENCY
8580   NEXT I
8590   Afreq=Xmin                             !RESET START FREQUENCY
```

```
8600  Y=(S=4)                                            !CHECK FOR THE S22 FLAG
8610  IF Y THEN GOTO 8640                                !IF SET, SKIP THE NEXT STATEMENT
8620  INPUT "Replace the THRU with the DUT. Press CONT.",Y
8630  GOTO 8650                                          !GO TO RETURN COMMAND
8640  INPUT "Replace the OPEN with the DUT. Press CONT.",Y
8650  RETURN                                             !RETURN TO TAKE MEASUREMENTS
8660                                                     ! FROM THE DEVICE UNDER TEST
8670  !
8680  OUTPUT 711;"ST5;"                                  !SET SWEEP TYPE TO CONTINUOUS WAVE
8690  Xmin=Cfreq                                         !DEFINES MINIMUM FREQUENCY FOR THE
8700                                                     ! LOWER END OF THE HORIZONTAL AXIS
8710                                                     ! (AND SAVES THE VALUE FOR START
8720                                                     ! FREQUENCY OF THE BANDWIDTH)
8730  FOR I=Ii TO N                                      !IF SAW DEVICE, LOOP BEGINS WITH
8740                                                     ! 2. OTHERWISE, LOOP BEGINS WITH 1
8750      Cfreq=(I-1)*Df+Xmin                            !INCREMENT FREQUENCY BY THE
8760                                                     ! DELTA FREQUENCY
8770      OUTPUT 711 USING 8780;Cfreq
8780      IMAGE "SFR;",DDD.DDDDDD,"MHz;"                 !SOURCE FREQUENCY STARTS AT MINIMUM
8790                                                     ! VALUE OF THE BANDWIDTH AND IS
8800                                                     ! ACCURATE TO ONE HERTZ
8810      OUTPUT 711;"TKM;FM1;DM1;"                      !TAKE MEASUREMENT, PUT IN ASCII
8820                                                     ! FORM, AND DUMP THE MAGNITUDE
8830                                                     ! MARKER FOR TRACE 1
8840      ENTER 711;Dn(I)                                !ENTER DATA INTO CALIBRATION
8850                                                     ! MAGNITUDE ARRAY, Dn
8860      OUTPUT 711;"TKM;FM1;DM2;"                      !TAKE MEASUREMENT, PUT IN ASCII
8870                                                     ! FORM, AND DUMP THE CALIBRATION
8880                                                     ! PHASE MARKER FOR TRACE 2
8890      ENTER 711;En(I)                                !ENTER DATA INTO THE CALIBRATION
8900                                                     ! PHASE ARRAY, En
8910  NEXT I
8920  Cfreq=Xmin                                         !RELOAD THE VALUE FOR THE START
8930                                                     ! FREQUENCY INTO Cfreq
8940  Y=(S=4)                                            !CHECK FOR THE S22 FLAG
8950  IF Y THEN GOTO 8980                                !IF SET, SKIP THE NEXT STATEMENT
8960  INPUT "Replace the THRU with the DUT. Press CONT.",Y
8970  GOTO 8990
8980  INPUT "Replace the OPEN with the DUT. Press CONT.",Y
8990  RETURN                                             !RETURN TO TAKE MEASUREMENTS FROM
9000                                                     ! THE DEVICE UNDER TEST
9010  !
9020  ! ONE PORT FULL CALIBRATION
9030  INPUT "Replace the DUT with the OPEN. Press CONT.",Y
9040  DISP "Please wait. Measurements are being taken."
9050  Y=(Du=1)                                           !CHECK THE "DUMP THE SCREEN" FLAG
9060  IF Y THEN GOTO 9150                                !IF SET, GOTO TAKE CALIBRATION
9070                                                     ! MEASUREMENTS
9080  Y=(Nu=1)                                           !CHECK THE "DEFINE N" FLAG
9090  IF Y THEN GOTO 9560                                !IF SET, GOTO TAKE CALIBRATION
9100                                                     ! MEASUREMENTS
9110  Y=(Fr=1)                                           !CHECK THE "DEFINE dF" FLAG
9120  IF Y THEN GOTO 10250                               !IF SET, GOTO TAKE CALIBRATION
9130                                                     ! MEASUREMENTS
9140  !
9150  OUTPUT 711;"SM2;TKM;FM1;DT1;"                      !SINGLE SWEEP, TAKE MEASUREMENT,
9160                                                     ! PUT INTO ASCII FORM, AND DUMP
9170                                                     ! TRACE 1
9180  ENTER 711 USING "#,F";D(*)                         !ENTER DATA INTO THE MATH
9190                                                     ! MAGNITUDE ARRAY, D
9200  OUTPUT 711;"SM2;TKM;FM1;DT2;"                      !SINGLE SWEEP, TAKE MEASUREMENT,
9210                                                     ! PUT INTO ASCII FORM, AND DUMP
9220                                                     ! TRACE 2
9230  ENTER 711 USING "#,F";E(*)                         !ENTER DATA INTO MATH PHASE
9240                                                     ! ARRAY, E
9250  GOSUB 6550                                         !GOT TO CHANGE TO REAL AND IMAG.
9260  MAT A=P                                            !STORE ARRAY P INTO ARRAY
9270                                                     ! GAMMA(OPEN,REAL)=A
9280  MAT B=O                                            !STORE ARRAY O INTO ARRAY
9290                                                     ! GAMMA(OPEN,IMAGINARY)=B
9300  INPUT "Replace the OPEN with the SHORT. Press CONT.",Y
9310  DISP "Measuring again. . ."
```

```
9320    OUTPUT 711;"SM2;TKM;FM1;DT1;"
9330    ENTER 711 USING "#,F";D(*)
9340    OUTPUT 711;"SM2;TKM;FM1;DT2;"
9350    ENTER 711 USING "#,F";E(*)
9360    GOSUB 6550                                  !GOTO CHANGE TO REAL AND IMAG.
9370    MAT C=P                                     !LOAD ARRAY P INTO ARRAY
9380                                                ! GAMMA(SHORT,REAL)=C
9390    MAT F=O                                     !LOAD ARRAY O INTO ARRAY
9400                                                ! GAMMA(SHORT,IMAGINARY)=F
9410    INPUT "Replace the SHORT with the reference LOAD (50 ohms). Press CONT.",Y
9420    DISP ". . .and again."
9430    OUTPUT 711;"SM2;TKM;FM1;DT1;"
9440    ENTER 711 USING "#,F";D(*)
9450    OUTPUT 711;"SM2;TKM;FM1;DT2;"
9460    ENTER 711 USING "#,F";E(*)
9470    GOSUB 6550                                  !GOTO CHANGE TO REAL AND IMAG.
9480    MAT G=P                                     !LOAD ARRAY P INTO ARRAY
9490                                                ! GAMMA(t,REAL)=G
9500    MAT H=O                                     !LOAD ARRAY O INOT ARRAY
9510                                                ! GAMMA(t,IMAGINARY)=H
9520    GOSUB 10880                                 !GO TO PERFORM CALCULATIONS
9530    RETURN                                      !RETURN TO TAKE MEASUREMENTS
9540                                                ! FROM THE DEVICE UNDER TEST
9550    !
9560    OUTPUT 711;"ST5;"                           !SET SWEEP TYPE TO CONTINUOUS WAVE
9570    Xmin=Afreq                                  !DEFINES MINIMUM FREQUENCY FOR THE
9580                                                ! LOWER END OF THE HORIZONTAL AXIS
9590                                                ! (SAVES THE VALUE OF THE START
9600                                                ! FREQUENCY)
9610    FOR I=1 TO N
9620        OUTPUT 711 USING 8430;Afreq
9630        IMAGE "SFR;",DDD.DDDDDD,"MHZ;"          !SOURCE FREQUENCY STARTS AT THE
9640                                                ! DEFINED START FREQUENCY
9650        OUTPUT 711;"TKM;FM1;DM1;"               !TAKE MEASUREMENTS, PUT INTO ASCII
9660                                                ! FORM, AND DUMP MAGNITUDE MARKER
9670                                                ! FROM TRACE 1
9680        ENTER 711;D(I)                          !ENTER DATA INTO MATH MAGNITUDE
9690                                                ! ARRAY, D
9700        OUTPUT 711;"TKM;FM1;DM2;"               !TAKE MEASUREMENT, PUT IN ASCII
9710                                                ! FORM, AND DUMP PHASE MARKER
9720                                                ! FROM TRACE 2
9730        ENTER 711;En(I)                         !ENTER DATA INTO MATH
9740                                                ! PHASE ARRAY, E
9750        Afreq=Afreq+Df                          !INCREMENT FREQUENCY BY THE
9760                                                ! CALCULATED DELTA FREQUENCY
9770    NEXT I
9780    Afreq=Xmin                                  !RELOAD START FREQUENCY INTO Afreq
9790    GOSUB 6550                                  !GOTO CHANGE TO REAL AND IMAG.
9790    MAT A=P                                     !STORE ARRAY P INTO ARRAY
9810                                                ! GAMMA(OPEN,REAL)=A
9820    MAT B=O                                     !STORE ARRAY O INTO ARRAY
9830                                                ! GAMMA(OPEN,IMAGINARY)=B
9840    INPUT "Replace the OPEN with the SHORT. Press CONT.",Y
9850    DISP "Measuring again . . ."
9860    Xmin=Afreq
9870    FOR I=1 TO N
9880        OUTPUT 711 USING 9890;Afreq
9890        IMAGE "SFR;",DDD.DDDDDD,"MHZ;"
9900        OUTPUT 711;"TKM;FM1;DM1;"
9910        ENTER 711;D(I)
9920        OUTPUT 711;"TKM;FM1;DM2;"
9930        ENTER 711;E(I)
9940        Afreq=Afreq+Df
9950    NEXT I
9960    Afreq=Xmin                                  !RELOAD STRAT FREQUENCY INTO Afreq
9970    GOSUB 6550                                  !GOTO CHANGE TO REAL AND IMAG.
9980    MAT C=P                                     !LOAD ARRAY P INTO ARRAY
9990                                                ! GAMMA(SHORT,REAL)=C
```

```
10000   MAT F=O                                          !LOAD ARRAY O INTO ARRAY
10010                                                    ! GAMMA(SHORT,IMAGINARY)=F
10020   INPUT "Replace the SHORT with the reference LOAD (50 ohms). Press CONT.",Y
10030   DISP ". . .and again."
10040   Xmin=Afreq
10050   FOR I=1 TO N
10060       OUTPUT 711 USING 10070;Afreq
10070      IMAGE "SFR;",DDD.DDDDDD,"MHZ;"
10080       OUTPUT 711;"TKM;FM1;DM1;"
10090       ENTER 711;D(I)
10100       OUTPUT 711;"TKM;FM1;DM2;"
10110       ENTER 711;E(I)
10120       Afreq=Afreq+Df                               !INCREMENT FREQUENCY BY THE
10130                                                    ! CALCULATED DELTA FREQUENCY
10140   NEXT I
10150   Afreq=Xmin                                       !RELOAD START FREQUENCY INTO Afreq
10160   GOSUB 6550                                       !GOTO CHANGE TO REAL AND IMAG.
10170   MAT G=P                                          !LOAD ARRAY P INTO ARRAY
10180                                                    ! GAMMA(t,REAL)=G
10190   MAT H=O                                          !LOAD ARRAY O INTO ARRAY
10200                                                    ! GAMMA(t,IMAGINARY)=H
10210   GOSUB 10800                                      !GO TO PERFORM CALCULATIONS
10220   RETURN                                           !RETURN TO TAKE MEASUREMENTS FROM
10230                                                    ! THE DEVICE UNDER TEST
10240   !
10250   OUTPUT 711;"ST5;"                                !SET SWEEP TYPE TO CONTINUOUS WAVE
10260   Xmin=Cfreq                                       !DEFINES MINIMUM FREQUENCY FOR THE
10270                                                    ! LOWER END OF THE HORIZONTAL AXIS
10280                                                    ! (AND SAVES THE VALUE FOR THE
10290   FOR I=1 TO N
10300       OUTPUT 711 USING 10310;Cfreq
10310       IMAGE "SFR;",DDD.DDDDDD,"MHz;"               !SOURCE FREQUENCY STARTS AT MINIMUM
10320       OUTPUT 711;"TKM;FM1;DM1;"                    !TAKE MEASUREMENT, PUT INTO ASCII
10330                                                    ! FORM, DUMP THE MAGNITUDE MARKER
10340                                                    ! FROM TRACE 1
10350       ENTER 711;D(I)                               !ENTER DATA INTO MATH MAGNITUDE
10360                                                    ! ARRAY, D
10370       OUTPUT 711;"TKM;FM1;DM2;"                    !TAKE MEASUREMENT, PUT INTO ASCII
10380                                                    ! FORM, DUMP PHASE MARKER FROM
10390                                                    ! TRACE 2
10400       ENTER 711;E(I)                               !ENTER DATA INTO THE MATH PHASE
10410                                                    ! ARRAY, E
10420       Cfreq=Cfreq+Df                               !INCREMENT THE FREQUENCY BY THE
10430                                                    ! DEFINED DELTA FREQUENCY
10440   NEXT I
10450   Cfreq=Xmin                                       !RELOAD START FREQUENCY INTO Cfreq
10460   GOSUB 6550                                       !GOTO CHANGE TO REAL AND IMAG.
10470   MAT A=P                                          !STORE ARRAY P INTO ARRAY
10480                                                    ! GAMMA(OPEN,REAL)=A
10490   MAT B=O                                          !STORE ARRAY O INTO ARRAY
10500                                                    ! GAMMA(OPEN,IMAGINARY)=B
10510   INPUT "Replace the OPEN with the SHORT. Press CONT.",Y
10520   DISP "Measuring again."
10530   Xmin=Cfreq
10540   FOR I=1 TO N
10550       OUTPUT 711 USING 10560;Cfreq
10560       IMAGE "SFR;",DDD.DDDDDD,"MHz;"
10570       OUTPUT 711;"TKM;FM1;DM1;"
10580       ENTER 711;D(I)
10590       OUTPUT 711;"TKM;FM1;DM2;"
10600       ENTER 711;E(I)
10610       Cfreq=Cfreq+Df
10620   NEXT I
10630   Cfreq=Xmin                                       !RELOAD START OF BAND INTO Cfreq
10640   GOSUB 6550                                       !GOTO CHANGE TO REAL AND IMAG.
10650   MAT C=P                                          !LOAD ARRAY P INTO ARRAY
10660                                                    ! GAMMA(SHORT,REAL)=C
10670   MAT F=O                                          !LOAD ARRAY O INTO ARRAY
10680                                                    ! GAMMA(SHORT,IMAGINARY)=F
10690   INPUT "Replace the SHORT with the reference LOAD (50 ohms). Press CONT.",Y
10700   DISP ". . .and again."
10710   Xmin=Cfreq
```

```
10720  FOR I=1 TO N
10730      OUTPUT 711 USING 10740;Cfreq
10740      IMAGE "SFR;",DDD.DDDDDD,"MHz;"
10750      OUTPUT 711;"TKM;FM1;DM1;"
10760      ENTER 711;D(I)
10770      OUTPUT 711;"TKM;FM1;DM2;"
10780      ENTER 711;E(I)
10790      Cfreq=Cfreq+Df
10800  NEXT I
10810  Cfreq=Xmin                         !RELOAD BAND START FREQUENCY
10820  GOSUB 6550                         !GOTO CHANGE TO REAL AND IMAG.
10830  MAT G=P                            !LOAD ARRAY P INTO ARRAY
10840                                     ! GAMMA(t,REAL)=G
10850  MAT H=O                            !LOAD ARRAY O INTO ARRAY
10860                                     ! GAMMA(t,IMAGINARY)=H
10870  !
10880  ! FIND Tf (THE CORRECTION FACTOR FOR TRANSMISSION.) IT IS GIVEN
10890  ! BY:  Tf=(2GsGo-Gt(Gs+GO))/(Gs-Go)
10900  DISP "Calculating the correction factor for transmission. . ."
10910  !
10920  MAT Dn=C+A                         !Gsr+Gor
10930  MAT En=F+B                         !Gsi+Goi
10940  MAT P=G                            !PREPARE Gtr FOR CONVERSION
10950  MAT O=H                            !PREPARE Gti FOR CONVERSION
10960  GOSUB 6890                         !GOTO RECTANGULAR-TO-POLAR SUBR.
10970  MAT G=D                            !Gt MAG
10980  MAT H=E                            !Gt PHASE
10990  MAT P=Dn                           !PREPARE FOR CONVERSION
11000  MAT O=En                           !PREPARE FOR CONVERSION
11010  GOSUB 6890                         !GOTO RECTANGULAR-TO-POLAR SUBR.
11020  MAT Dn=D                           !(Gs+Go) MAG
11030  MAT En=E                           !(Gs+Go) PHASE
11040  MAT Dn=Dn+G                        !2ND TERM OF NUMERATOR;LOG. MAG.
11050  MAT En=En+H                        !2ND TERM OF NUM.;POLAR PHASE, RAD.
11060  MAT P=C                            !PREPARE Gsr FOR CONVERSION
11070  MAT O=F                            !PREPARE Gsi FOR CONVERSION
11080  GOSUB 6890                         !GOTO RECTANGULAR-TO-POLAR SUBR.
11090  MAT C=D                            !Gs MAG.
11100  MAT F=E                            !Gs PHASE
11110  MAT P=A                            !PREPARE Gor FOR CONVERSION
11120  MAT O=B                            !PREPARE Goi FOR CONVERSION
11130  GOSUB 6890                         !GOTO RECTANGULAR-TO-POLAR SUBR.
11140  MAT A=D                            !Go MAG.
11150  MAT B=E                            !Go PHASE
11160  FOR I=1 TO N
11170    P(I)=2                           !DEFINE P ARRAY TO BE 2, RECT.,REAL
11180    O(I)=0                           !DEFINE O ARRAY TO BE 0, RECT.,IMAG
11190  NEXT I
11200  GOSUB 6890                         !GOTO RECTANGULAR-TO-POLAR SUBR.
11210  MAT D=D+C                          !2*Gs,LOG. MAG.
11220  MAT D=D+A                          !2*Gs*Go,LOG. MAG.
11230  MAT E=E+F                          !2*Gs,PHASE,RAD.
11240  MAT E=E+B                          !2*Gs*Go,PHASE,RAD.
11250  GOSUB 6720                         !GOTO POLAR-TO-RECTANGULAR SUBR.
11260  MAT M=P                            !FIRST TERM OF NUMERATOR;RECT.REAL
11270  MAT N=O                            !FIRST TERM OF NUMERATOR;RECT.IMAG.
11280  MAT D=Dn                           !PREPARE 2ND TERM OF NUMERATOR
11290  MAT E=En                           !FOR CONVERSION
11300  GOSUB 6720                         !GOTO POLAR-TO-RECTANGULAR SUBR.
11310  MAT P=M-P                          !NUMERATOR; RECT. REAL
11320  MAT O=N-O                          !NUMERATOR; RECT. IMAG.
11330  GOSUB 6890                         !GOTO RECTANGULAR-TO-POLAR SUBR.
11340  MAT M=D                            !NUMERATOR; POLAR LOG. MAG.
11350  MAT N=E                            !NUMERATOR; POLAR PHASE RADIANS
11360  MAT D=A                            !PREPARE Go MAG. FOR CONVERSION
11370  MAT E=B                            !PREPARE Go PHASE FOR CONVERSION
11380  GOSUB 6720                         !GOTO POLAR-TO-RECTANGULAR SUBR.
11390  MAT A=P                            !Gor
11400  MAT B=O                            !Goi
11410  MAT D=C                            !PREPARE Gs MAG. FOR CONVERSION
11420  MAT E=F                            !PREPARE Gs PHASE FOR CONVERSION
11430  GOSUB 6720                         !GOTO POLAR-TO-RECTANGULAR SUBR.
```

```
11440  MAT C=P                                      !Gsr
11450  MAT F=O                                      !Gsi
11460  MAT P=C-A                                    !DENOMINATOR; RECT. REAL
11470  MAT O=F-B                                    !DENOMINATOR; RECT. IMAG.
11480  GOSUB 6890                                   !GOTO RECTANGULAR-TO-POLAR SUBR.
11490  MAT M=M-D                                    !Tf IN POLAR FORM; LOG. MAGNITUDE
11500  MAT N=N-E                                    !Tf IN POLAR FORM; PHASE (RADIANS)
11510  !
11520  ! FIND Sf (FACTOR FOR SOURCE MATCH.) IT IS GIVEN
11530  ! BY: Sf=(2Gt-Gs-Go)/(Gs-Go)
11540  DISP "Calculating the factor for source match. . ."
11550  FOR I=1 TO N
11560      P(I)=2                                   !DEFINE P ARRAY = 2,RECT.REAL
11570      O(I)=0                                   !DEFINE O ARRAY = 0,RECT.IMAG.
11580  NEXT I
11590  GOSUB 6890                                   !GOTO RECTANGULAR-TO-POLAR SUBR.
11600  MAT D=D+G                                    !PREPARE 2*Gt MAG FOR CONVERSION
11610  MAT E=E+H                                    !PREPARE 2*Gi PHASE FOR CONVERSION
11620  GOSUB 6720                                   !GOTO POLAR-TO-RECTANGULAR SUBR.
11630  MAT G=P                                      !2*Gtr
11640  MAT H=O                                      !2*Gti
11650  MAT Q=C+A                                    !Gs+Go;RECT.REAL
11660  MAT R=F+B                                    !Gs+Go;RECT.IMAG.
11670  MAT Dn=G                                     !2*Gtr
11680  MAT En=H                                     !2*Gti
11690  MAT P=Dn-Q                                   !NUMERATOR;RECT. REAL
11700  MAT O=En-R                                   !NUMERATOR;RECT. IMAG.
11710  GOSUB 6890                                   !GOTO RECTANGULAR-TO-POLAR
11720  MAT Dn=D                                     !NUMERATOR;POLAR LOG. MAG.
11730  MAT En=E                                     !NUMERATOR;POLAR PHASE,RADIANS
11740  MAT Q=C-A
11750  MAT R=F-B
11760  MAT P=Q                                      !PREPARE DENOMINATOR FOR CONVERSION
11770  MAT O=R                                      !PREPARE DENOMINATOR FOR CONVERSION
11780  GOSUB 6890                                   !GOTO RECTANGULAR-TO-POLAR SUBR.
11790  MAT Q=Dn-D                                   !Sf;POLAR,LOG. MAGNITUDE
11800  MAT R=En-E                                   !Sf;POLAR,PHASE,RADIANS
11810  MAT Dn=M                                     !Tf;POLAR,LOG. MAGNITUDE
11820  MAT En=N                                     !Tf;POLAR,PHASE,RADIANS
11830  !
11840  ! NOTE: THE CORRECTION FACTOR FOR DIRECTIVITY IS GIVEN BY Gt
11850  !
11860  INPUT "Now replace the DUT. Press CONT.",Y
11870  RETURN                                       !RETURN TO TAKE MEASUREMENTS
11880                                               ! FROM THE DEVICE UNDER TEST
11890  !
11900  ! THE FOLLOWING SECTION FINDS THE CORRECTED MEASUREMENT. IT IS GIVEN
11910  ! BY S11=(Mmeas-D)/(Sf*Mmeas+Tf)
11920  DISP "Calculating the corrected measurement for S11. . ."
11930  Y=(Re=1)                                     !CHECK ERROR RUN ONCE THROUGH FLAG
11940  IF Y THEN GOTO 11960                         !IF SET, GOTO RELOAD Sf
11950  GOTO 11980                                   !ELSE, CONTINUE
11960  MAT Q=P                                      !RELOAD Sf INTO ARRAYS
11970  MAT R=O                                      !Q AND R
11980  ! Mmeas=D and E in polar form at this point
11990  GOSUB 6550                                   !GOTO POLAR-TO-RECTANGULAR SUBR.
12000  MAT A=P                                      !Mmeas;RECT.,REAL
12010  MAT B=O                                      !Mmeas;RECT.,IMAG.
12020  Y=(Re=1)                                     !CHECK ERROR RUN ONCE THROUGH FLAG
12030  IF Y THEN GOTO 12080                         !IF SET, SKIP NEXT MATH STEP
12040  FOR I=1 TO N
12050      G(I)=.5*G(I)                             !.5*2*Gtr = Gtr
12060      H(I)=.5*H(I)                             !.5*2*Gti = Gti
12070  NEXT I
12080  MAT P=A-G                                    !NUMERATOR; RECT.REAL
12090  MAT O=B-H                                    !NUMERATOR; RECT.IMAG.
12100  GOSUB 6890                                   !GOTO RECTANGULAR-TO-POLAR SUBR.
12110  MAT C=D                                      !NUMERATOR; POLAR, LOG. MAG.
12120  MAT F=E                                      !NUMERATOR; POLAR, PHASE, RADIANS
12130  MAT P=A                                      !PREPARE Mmeas FOR CONVERSION
12140  MAT O=B                                      !PREPARE Mmeas FOR CONVERSION
12150  GOSUB 6890                                   !GOTO RECTANGULAR-TO-POLAR SUBR.
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12160  MAT A=D                                    !Mmeas; POLAR, LOG. MAG.
12170  MAT B=E                                    !Mmeas; POLAR, PHASE, RADIANS
12180  MAT D=Q+A                                  !Sf*Mmeas; POLAR, LOG. MAG.
12190  MAT E=R+B                                  !Sf*Mmeas; POLAR, PHASE, RADIANS
12200  GOSUB 6720                                 !GOTO POLAR-TO-RECTANGULAR SUBR.
12210  MAT A=P                                    !Sf*Mmeas;RECT.REAL
12220  MAT B=O                                    !Sf*Mmeas;RECT IMAG.
12230  MAT D=Dn                                   !PREPARE Tf FOR CONVERSION
12240  MAT E=En                                   !PREPARE Tf FOR CONVERSION
12250  GOSUB 6720                                 !GOTO POLAR-TO-RECTANGULAR
12260  MAT P=P+A                                  ! +Tf (RECT.REAL)
12270  MAT O=O+B                                  ! +Tf (RECT.IMAG.)
12280  GOSUB 6890                                 !GOTO RECTANGULAR-TO-POLAR SUBR.
12290  MAT C=C-D                                  !S11; POLAR, LOG. MAG.
12300  MAT F=F-E                                  !S11; POLAR, PHASE, RADIANS
12310  FOR Z=1 TO N
12320      A=180/PI
12330      F(Z)=F(Z)*A                            !S11;POLAR,PHASE,DEGREES
12340      C(Z)=20*C(Z)                           !S11;POLAR,MAG.,dB
12350  NEXT Z
12360  Y=(E=1)                                    !CHECK THE ERROR RUN FLAG
12370  IF Y THEN GOTO 12390                       !IF SET, GO TO CHECK ANOTHER FLAG
12380  GOTO 12440                                 !ELSE, CONTINUE
12390  Y=(Re=0)                                   !CHECK ERROR RUN ONCE THROUGH FLAG
12400  IF Y THEN GOTO 12420                       !IF SET, GOTO STORE Sf
12410  GOTO 12440                                 !ELSE, CONTINUE
12420  MAT P=Q                                    !STORE Sf DURING SECOND SWEEP
12430  MAT O=R                                    !STORE Sf DURING SECOND SWEEP
12440  MAT Q=C                                    !S11
12450  MAT R=F                                    !S11
12460  RETURN
12470  !
12480  ! CHECK FOR 360 DEGREE PHASE SHIFT AND CENTER
12490  FOR I=1 TO N
12500    Y=(E(I)<180)
12510    IF Y THEN GOTO 12540
12520    E(I)=E(I)-360
12530    GOTO 12500
12540    Y=(E(I)>180)
12550    IF Y THEN GOTO 12580
12560    E(I)=E(I)+360
12570    GOTO 12540
12580  NEXT I
12590  RETURN
12600  !
12610  ! THIS SUBROUTINE WRITES THE RESULTS TO THE HARD DISK
12620  ! FOR FUTURE FAST FOURIER TRANSFORM
12630  INPUT "Would you like to save these results?",X$
12640  IF X$="Y" THEN GOTO 12660
12650  IF X$="N" THEN GOTO 12840
12660  INPUT "Enter filename.",N$
12670  FOR I=1 TO N-1
12680    Offset=0                                 !THIS SECTION CALCULATES THE
12690    IF C(I+1)>C(I) THEN Offset=360           !GROUP DELAY
12700    D(I)=-1*(C(I+1)-C(I)-Offset)/(Df*360)
12710  NEXT I
12720  Dmin=Df/2                                  !MINIMUM GROUP DELAY
12730  Dmax=(N-2)*Df+Dmin                         !MAXIMUM GROUP DELAY
12740  ASSIGN #1 TO N$&"F:A6",File                !ATTEMPT TO OPEN FILE
12750  IF File=0 THEN GOTO 12780                  !CHECK FOR FILE EXISTENCE
12760  CREATE N$&"F:A6",33,2048                   !CREATE FILE, IF NONEXISTENT
12770  ASSIGN #1 TO N$&"F:A6"                     !OPEN, AFTER CREATING FILE
12780  PRINT #1;N,B(*),C(*),Dfreq,1               !PRINT NUMBER OF POINTS,MAGNITUDE,
12790                                             ! PHASE,HIGHEST FREQUENCY,
12800                                             ! AVERAGING FACTOR
12810  PRINT #1;D(*),Dmin,Dmax                    !PRINT GROUP DELAY, MINIMUM AND
12820                                             ! MAXIMUM GROUP DELAY
12830  ASSIGN #1 TO *                             !CLOSE THE FILE
12840  RETURN                                     !RETURN TO PROGRAM
```

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VITA

Sallie Layton Douglas received her A.D.N. from Greenville Technical College, Greenville, S.C. in 1976 and her B.S.E. with an option in electrical engineering from the University of Central Florida in 1985.

She spent 1976-1982 as a Registered Nurse in surgery at Greenville General Hospital. While there she was promoted to Senior Nurse with a specialty in Neurosurgery.

In 1982, Ms. Douglas returned to her hometown of Orlando, Fl. to begin her studies in engineering. She has continued her nursing career on a part time basis in surgery at Orlando Regional Medical Center. She worked as a student assistant for the Mechanical Engineering Department in 1983-84 and was awarded the Florida Engineering Society scholarship for UCF in 1984. In 1985-86 she was employed by Martin Marietta Orlando Aerospace as a research and development technician in simulation. She is now on an Ed. L.O.A. from Martin Marietta.

Ms. Douglas began her thesis research in 1986. She completed her Masters Degree with an option in electrical engineering in 1987 and wishes to pursue a career in which she can use her medical background along with her engineering degree.

Ms. Douglas is a member of Tau Beta Pi (Service Award, '85), Eta Kappa Nu (Secr., '85-87), IEEE, Mensa, Cousteau Society, Rosalind Club, and Republican National Committee. She was listed in 1987's Who's Who Among Students and is an Usher, Youth Ministry Counselor, and Senior Minister Research Assistant at the First Presbyterian Church, Orlando, Fl.